OBSERVATIONS OF BREAKUP IN THE ATHABASCA RIVER BASIN UPSTREAM OF FORT McMURRAY, ALBERTA, 1984

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OBSERVATIONS OF BREAKUP IN THE ATHABASCA RIVER BASIN UPSTREAM OF FORT McMURRAY, ALBERTA, 1984

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ABSTRACT

Fort McMurray, Alberta is located on the Athabasca River at the confluence of the Clearwater River. When ice jams form downstream of the confluence, a flood condition may result. To add to the understanding of the behavior of these jams, this report summarizes the winter ice conditions, breakup observations, and ice jam analysis for the 1984 breakup.

After a slightly milder than normal winter, during which the precipitation was about 35 percent of normal, breakup occurred without serious flooding. On the observed tributaries, the Little Paddle River was the first to react to runoff from snowmelt. The Paddle River, although affected by outflows from the Paddle River Dam, reacted after the Little Paddle River, followed closely by the Pembina River. The runoff was insufficient to produce an intense breakup on the Athabasca River. Instead, the river broke up in isolated reaches in an overmature condition.

An ice run developed in the reach between Grande Rapids and Fort McMurray and culminated in the formation of an ice jam upstream of MacEwan Bridge. This jam remained in place for only about two hours, achieved a length of 9.5 km, a maximum stage of 6.5 m, and a thickness of at least 4.1 m at a discharge of about 650 m^3/s. Analysis showed that the Manning's roughness of the jam underside was in the order of 0.070 to 0.10 and the dimensionless coefficient of internal friction varied betwen 1.2 and 1.5.

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ACKNOWLEDGEMENTS

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INTRODUCTION

The City of Fort McMurray, Alberta (figure 1) is situated on the Athabasca River at the confluence of the Clearwater River. Ice jams, which have been intermittently documented since 1875 (Blench, 1963), often form downstream of the confluence and cause serious flooding within the community. The most recent of these events occurred in 1979 (Doyle and Andres, 1979). Observations have shown that these large flood-producing jams are similar from year to year and they are amenable to analysis (Andres and Doyle, 1984).

To mitigate potential ice jam related flood damages, an operational system is necessary to forecast the occurrence and severity of ice jamming. For this to be possible, an understanding of the breakup process upstream of Fort McMurray and its relation to snow pack, ice, and meteorologic characteristics during the spring melt period is necessary. This understanding can be improved by the observation and documentation of breakup in the Athabasca River basin upstream of Fort McMurray (Andres and Rickert, 1984). A rationalization of how the snow pack levels and temperatures affect the progression of breakup from the small upstream tributaries, such as the Little Paddle River, down to Fort McMurray may then result. Ice jams, if they occur, are also monitored to add to the data base to allow an improved understanding of their characteristics.

This report describes the 1983 freeze-up characteristics, the winter ice conditions, and the 1984 breakup at Fort McMurray. The breakup progression from the Little Paddle River basin (figure 2) to the Athabasca River at Fort McMurray is also documented, with particular attention paid to the sequence of events between Crooked Rapids and Fort McMurray. The breakup on the Clearwater River and the Christina River also is discussed briefly.

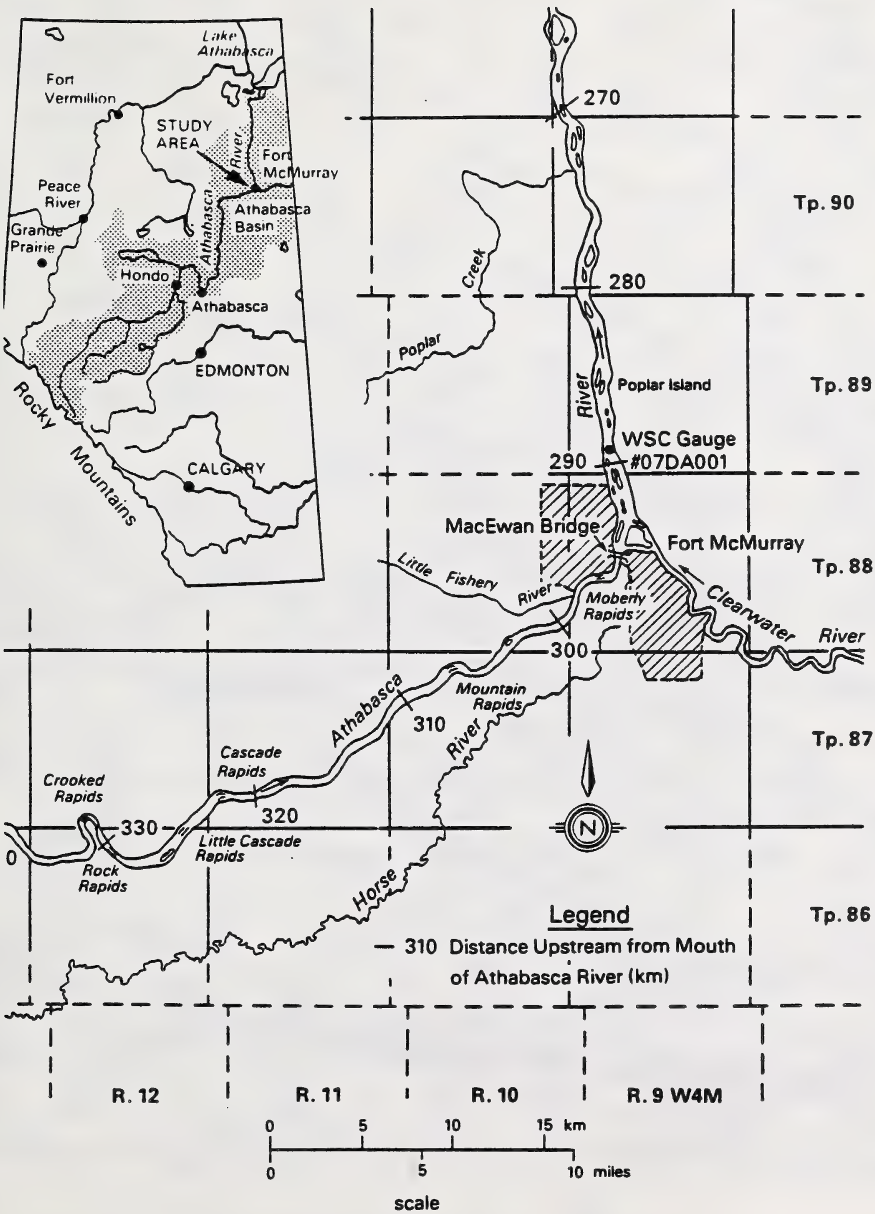

Figure 1. Location plan and study area

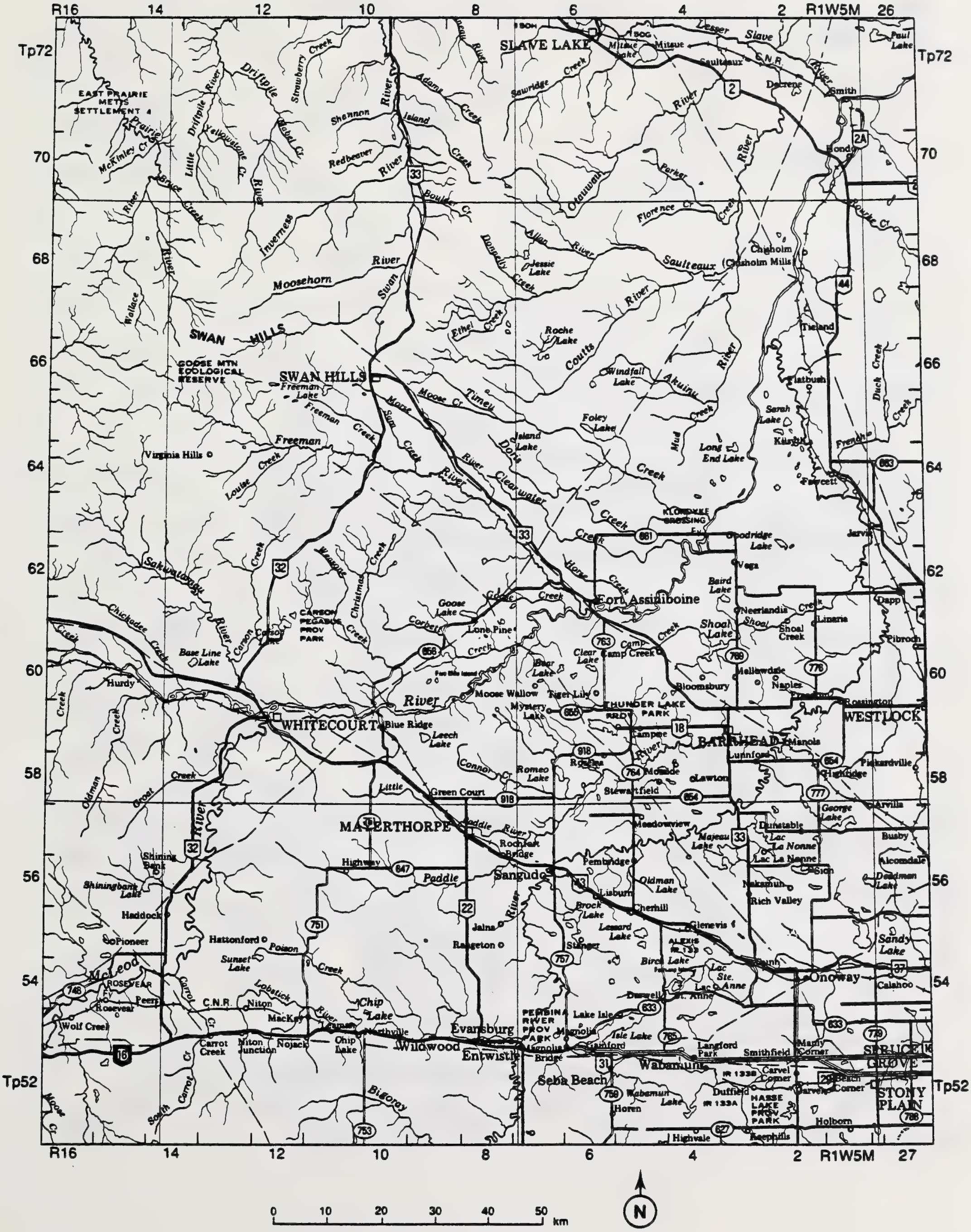

Figure 2a. Plan of portions of the Athabasca River basin upstream of Fort McMurray

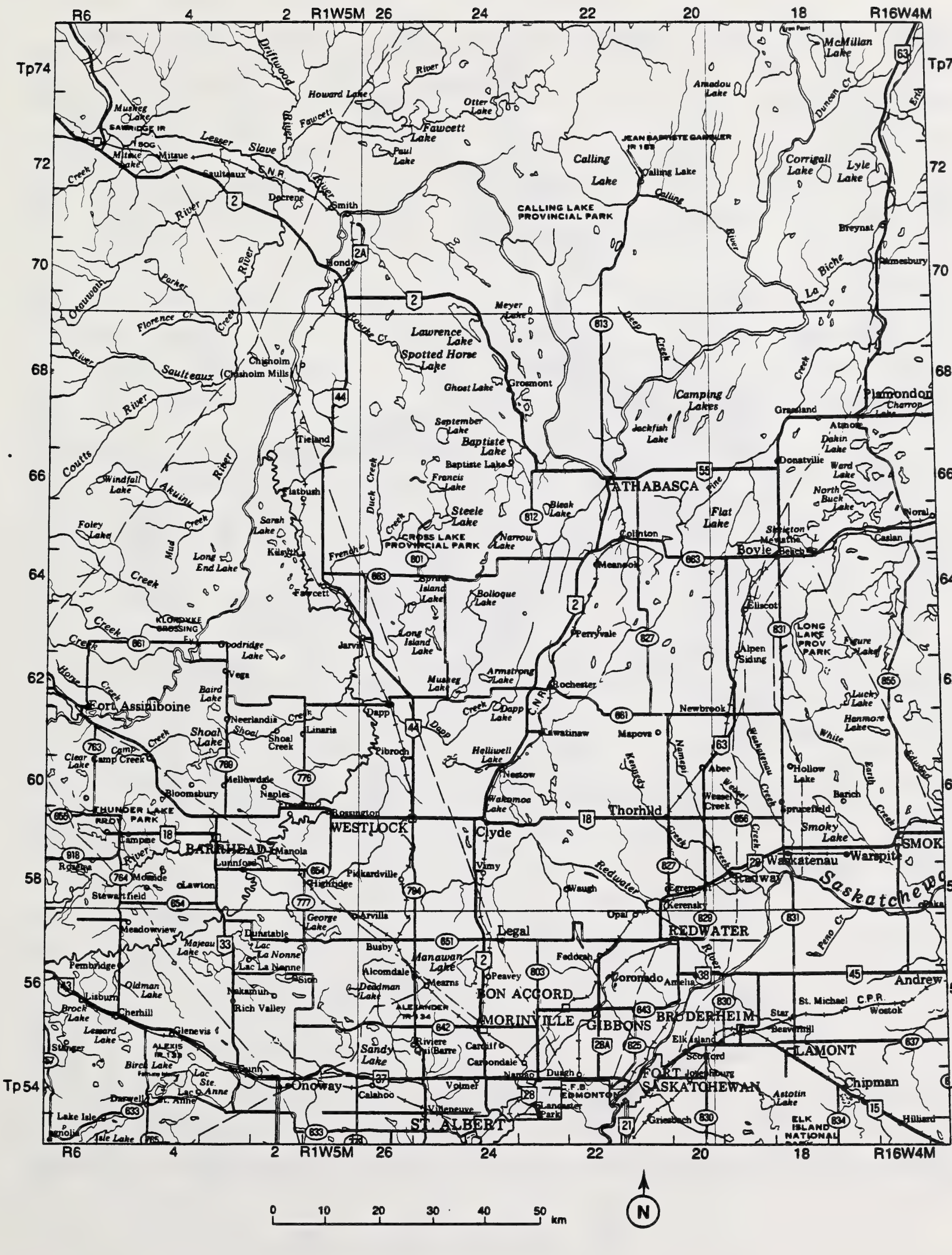

Figure 2b. Plan of portions of the Athabasca River basin upstream of Fort McMurray

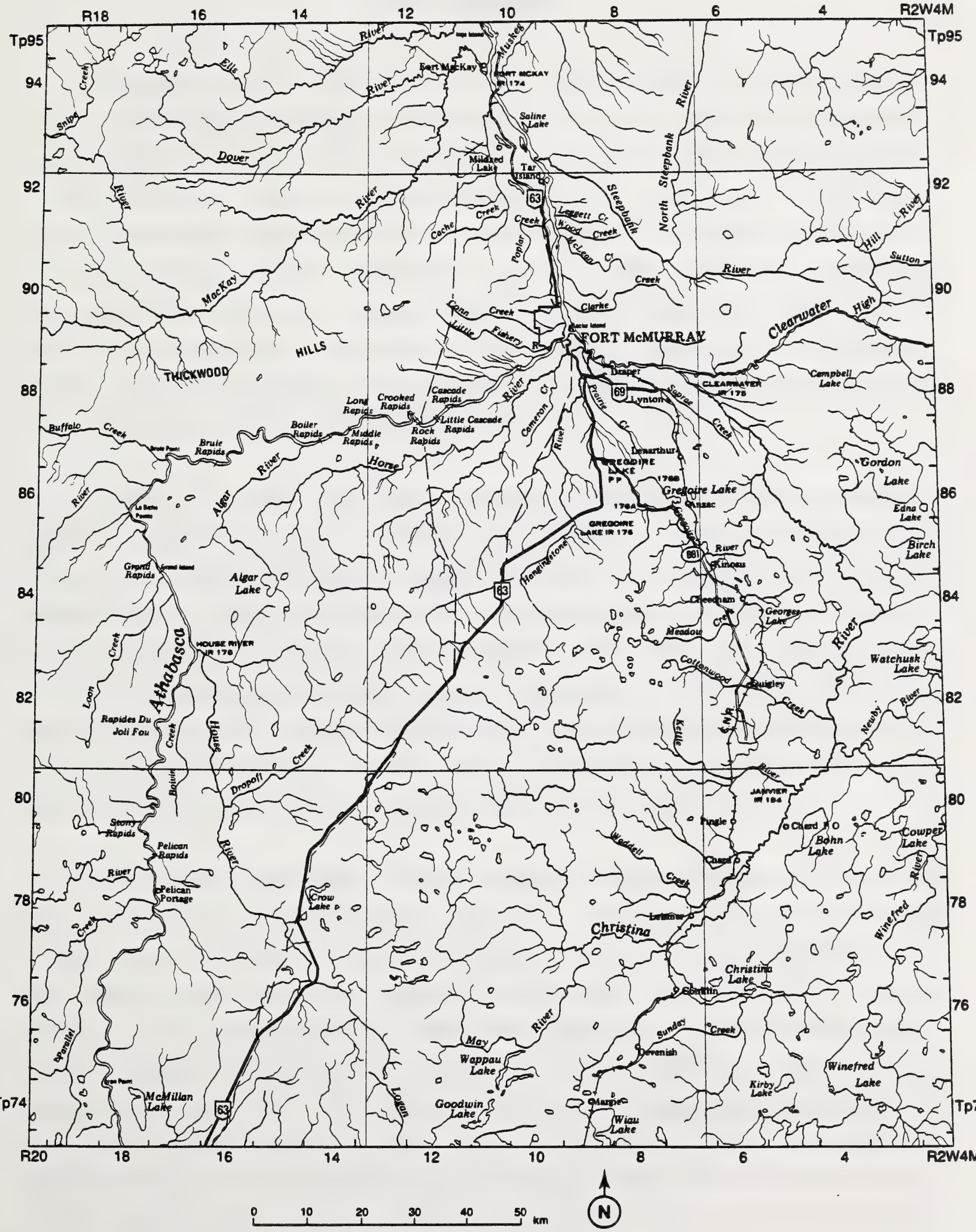

Figure 2c. Plan of portions of the Athabasca River basin upstream of Fort McMurray

FREEZE-UP DOWNSTREAM OF FORT McMURRAY

Freeze-up on the Athabasca River downstream of Fort McMurray results from the upstream progression of the ice cover by the juxtaposition of ice floes. Frazil produced in the turbulent rapids upstream of Fort McMurray forms into pans and/or rafts. Lodgement or bridging occurs somewhere downstream of the Water Survey of Canada (WSC) gauge and the cover progresses upstream from that point. Whether shoving at the gauge occures or not depends on the local temperature and rate at which ice accumulates at the head of the cover. Upstream of the MacEwan Bridge, where the channel slope increases dramatically, shoving appears to be the predominant form of cover formation.

In 1983, a stable ice cover formed at the WSC winter measurement section (location given in Andres and Rickert, 1984) on November 25 (figure 3) after 20 days of sub-zero mean daily temperatures and 82 degree days of freezing (figure 4). The discharge just prior to freeze-up was estimated by WSC to be approximately 480 m^3/s at a gauge height of 1.8 m (elevation 237.6 m). Upon formation of the cover, the river level increased to a maximum of 238.55 m and averaged about 238.4 m for the four days following. At the time of the stable cover formation, the mean daily air temperature at Fort McMurray was about -12°C.

Equilibrium conditions at the summer discharge measuring section were achieved at a Froude number of 0.11. This relatively high Froude number suggests that the cover thickness was governed by instability at the head of the cover, as opposed to internal instability of the pack itself. It is interesting to note that freeze-up in 1982 occurred at a Froude number of 0.08 for a mean daily air temperature which ranged between 0°C and -8°C. This considerably warmer temperature may explain the lower Froude number in 1982. It may be possible that the lower air temperatures in 1983 contributed to large ice floes arriving at the head of the cover. This made it more difficult for the ice to be entrained under the ice cover and resulted in an ice cover formed at a higher Froude number.

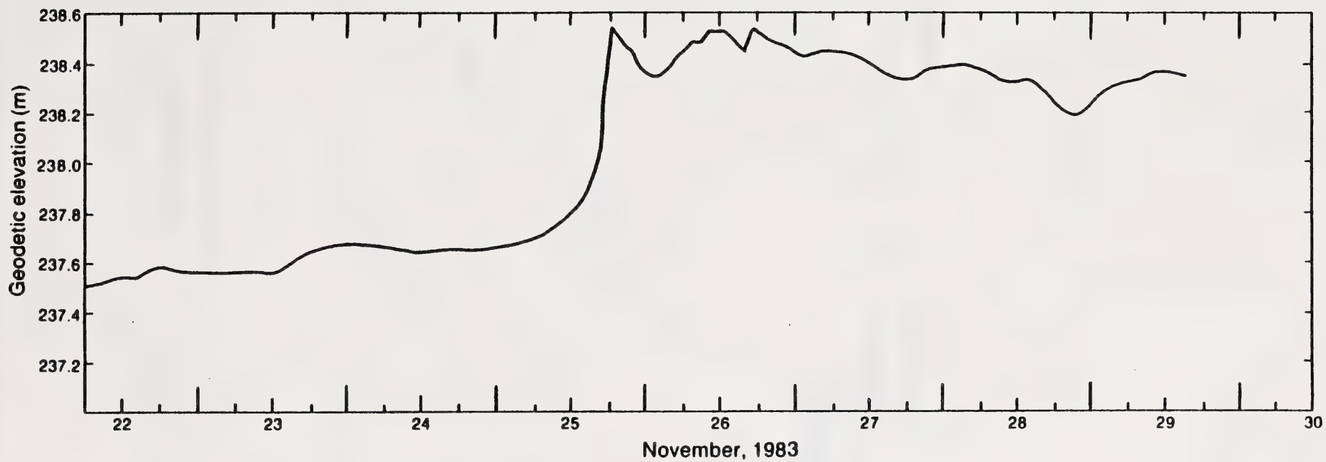

Figure 3. Freeze-up gauge heights at WSC Gauge #07DA001, Athabasca River downstream of Fort McMurray

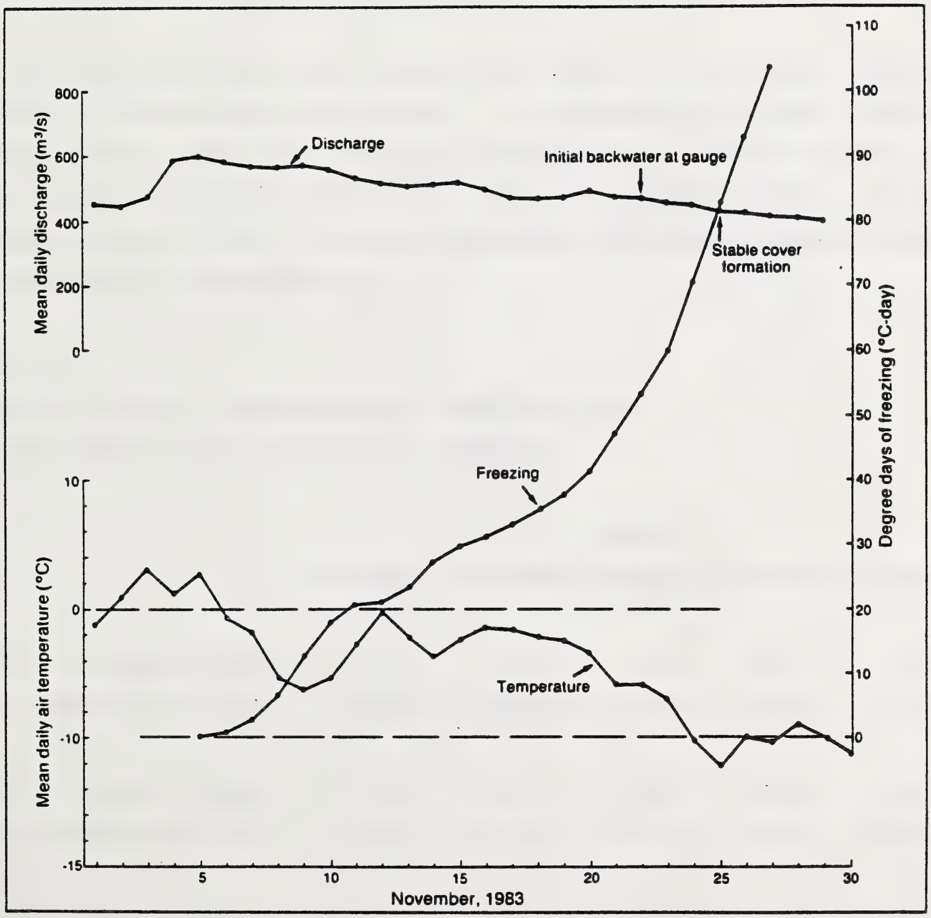

Figure 4. Meteorological and hydraulic conditions during freeze-up of the Athabasca River downstream of Fort McMurray

WINTER METEOROLOGIC CONDITIONS AND ICE THICKNESS

From November to March inclusive, the mean temperature at Fort McMurray for the winter of 1983/84 was -11.1°C. This was 3.3°C warmer than normal and 2.1°C warmer than the winter of 1982/83 (Andres and Rickert, 1984). With the exception of December, which had a mean monthly temperature of -22.3°C (5.3°C below normal), most of the winter temperatures were considerably above normal (table 1).

The total precipitation for the five months was 76.6 mm, which was 35.8 mm or 32 percent below normal. In comparison to the winter of 1982/83, there were 6.2 mm less precipitation. Precipitation was considerably less than normal in all the winter months (table 1) except November, when 32.8 mm of water equivalent (30 percent above normal) was recorded at Fort McMurray.

Table 1.
Summary of Monthly Temperature and Percipitation
at Fort McMurray for the Winter of 1983-84

	Month				
	November	December	January	February	March
Monthly Average Maximum Daily Temperature (°C)	-2.3 (-3.5)[a]	17.9 (-12.2)	-9.7 (-16.5)	-0.5 (-9.0)	1.2 (-2.2)
Monthly Average Minimum Daily Temperature (°C)	-7.0 (-12.7)	26.7 (-21.7)	-22.6 (-27.1)	-22.6 (-21.8)	-12.2 (16.1)
Monthly Average Mean Daily Temperature (°C)	-4.7 (-8.2)	-22.3 (-17.0)	-16.2 (-21.8)	- 6.6 (-15.4)	5.5 (9.2)
Total Precipitation (mm)	32.8 (25.2	7.9 (25.0)	19.9 (22.7)	8.8 (18.8)	7.2 (20.7)

[a] bracketed values indicate normal conditions.

Ice thickness characteristics are available from two sources of data. Measurement by WSC at their gauge downstream of Fort McMurray provide thickness and roughness estimates at three different times during the winter (table 2).

Table 2.

Hydraulic Characteristics at WSC Gauge #07DA001

Date	December 12	January 12	March 6
Discharge (m^3/s)	204	185	179
Gauge height (m)	2.503	2.167	2.220
Area (m^2)	368	271	271
Top width (m)	210	160	160
Mean depth (m)	1.75	1.69	1.69
Solid ice thickness (m)	0.37(1.0)[a]	0.71	0.81
Composite roughness[b]	0.041	0.031	0.032
Ice cover roughness[c]	0.056	0.040	0.041

[a] bracketed value indicates thickness of slush deposits which were encountered at about 25 percent of the holes.

[b] computed with a channel slope of 0.2 m/km.

[c] computed by the Sabaneev equation with a Manning's bed roughness of 0.021.

Of most interest in table 2 is the variation in the thickness and the roughness of the ice cover during the winter. A very low solid ice thickness of 0.37 m on December 12 more than doubles to 0.71 m by January 12 and then only increases an additional 15 percent by March 6. In comparison to data from previous years (Andres and Rickert, 1984), the December 12 ice thickness is the second lowest on record (1975-1984) but by January 12, the ice thickness had increased to above average (only two years have a greater ice thickness). This above average thickness was maintained into March. The very thin cover at formation, in addition to the warm November and early December and greater precipitation than normal in November, most likely led to the thin

December ice cover. Then, the colder than normal December probably resulted in the much thicker ice cover measurement in January.

It is interesting to note the presence of frazil under the ice cover during the December 12 measurement. The WSC records indicate accumulations up to 1.0 m in thickness. The origin of this frazil is only speculative but it could have come only from two sources. It could either be left from the frazil deposited during cover formation or it may have been randomly deposited from frazil being transported under the cover. Aerial photography indicates that the cover at the winter measurement section was uniform, so it would be anticipated that if the frazil was left over from freeze-up, the thickness of freeze-up would have been in the order of 1 m. This proves to be impossible because the overall stream roughness would have been unrealistically low. It is therefore most probable that the frazil was deposited after being transported from upstream, prior to the formation of a stable cover in those reaches.

The Manning's roughness of the ice cover decreased from 0.056 on December 12 to 0.031 on January 12. Following the January 12 measurement, the roughness remained relatively constant. Compared to the 1982-83 winter, the roughness of the cover was considerable greater than during previous winters. The presence of frazil on the December 12 measurement may account for the higher roughness on that date, however, this higher roughness was also calculated later in the winter when frazil at the section was not encountered. It is possible that an accumulation of frazil downstream of the section reduced the water surface slope and as a result the value of roughness was over estimated in the computation.

As in the previous year, the city of Fort McMurray also made ice thickness measurement at selected areas near the mouth of the Clearwater River and in the vicinity of MacEwan Bridge (figure 5). These measurements are summarized in table 3.

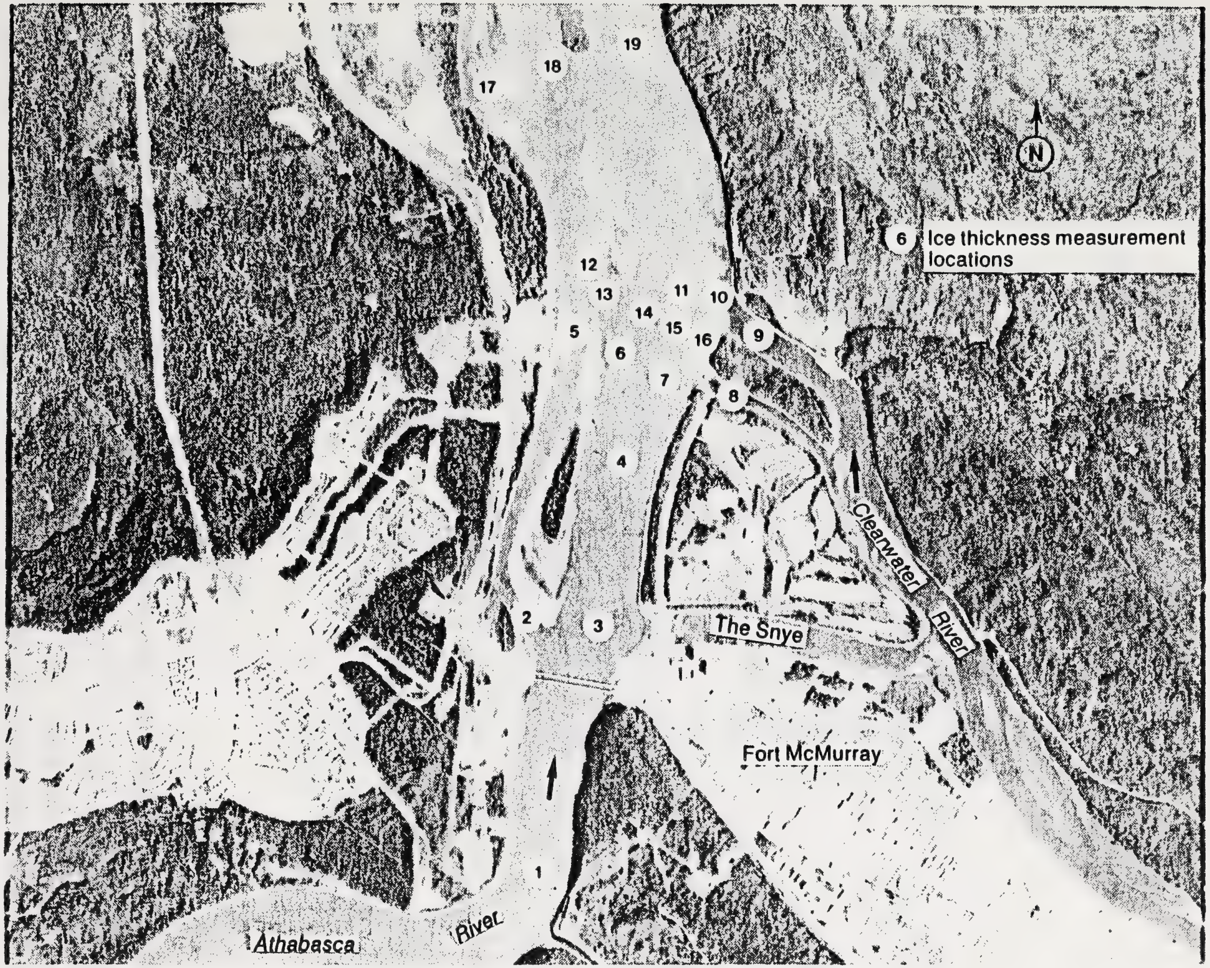

Figure 5. Ice thickness measurement locations on the Athabasca River at Fort McMurray

Table 3.
Ice Thickness Measurements on the Athabasca River near the Mouth of the Clearwater River

Location[a]	Ice Thickness (m)		
	February 2	March 12	March 26
1	1.20	0.9	0.9
2	-	0.9	1.1
3	-	0.9	0.9
4	-	0.9	0.9
5	1.2	1.2	0.8
6	0.9	0.9	1.1
7	0.9	0.9	1.1
8	-	0.9	0.9
9	0.9	0.9	0.8
10	0.9	0.9	0.6
11	0.2	1.0	0.9
12	0.9	0.9	0.8
13	0.9	1.1	0.9
14	1.2	1.2	0.9
15	0.9	0.9	0.8
16	0.9	0.9	0.8
17	0.6	0.3	Open Water
18	0.9	0.7	0.6
19	0.9	0.9	0.8

[a] see figure 7.

It is apparent that these measurements are approximate but the results are never-the-less of some value. By February 2, well after the coldest part of the winter, the majority of the ice cover had achieved a thickness of about 1 m. One notable exception is at location 11, where only 0.2 m of ice had developed. This location is right at the mouth of the Clearwater River and in the centre of the main Athabasca River channel. It is possible that an open lead developed at this location during freeze-up and the cover was slowly thickening in a static mode.

By March 12, the cover at this location had thickened to 1.0 m. The results also indicate that the cover upstream of the mouth of the Clearwater River (locations 1 to 7) tends to be somewhat thicker, probably due to the fact that a thicker cover is required to achieve stability because the channel slope is considerably steeper and the velocity is greater.

Once the maximum ice thickness was achieved by March 12, the ice thickness was reduced to an average of about 0.8 m by March 26, just prior to breakup. Even though the winter was milder than normal, relatively thick ice was produced. This may have been partially due to the lack of snow cover which reduced the insulation which would normally be available to limit the thickening of the ice. Overall, the ice thickness was not notably different than in any other year.

BREAKUP OBSERVATIONS

Observations of breakup were carried out on a basin-wide scale to study the manner in which the smaller basins affected the Athabasca River breakup pattern. These observations were made from fixed wing aircraft, helicopter, and by using Landsat imagery. Unfortunately, weather conditions were such that both aerial reconnaissance and the Landsat imagery proved difficult to utilize in the first ten days of April.

Little Paddle, Paddle, and Pembina Rivers

The winter of 1983-84 was relatively dry in comparison to normal years. Precipitation data in the plains areas east of Edson indicated that the total precipitation between November 1 and March 31 was about 65 percent of normal (Alberta Environment, 1984). Snow surveys indicate that on March 15, the snow cover on the ground in the plains area of the Athabasca River basin averaged about 26 cm or about 35 percent of normal. By March 31, the average snow depth had been reduced to 4 cm,

about 6 percent of normal. The Twin Lakes snow pillow, which is the only recording snow pillow in the plains area of the Athabasca River basin, recorded a peak snow water equivalent on March 15 of about 52 mm of water or about 50 cm of snow. This is about twice the average depth determined from snow surveys. However, the snow pillow did respond in the same manner on the rest of the basin, in that by March 31, the snow water equivalent was reduced to near zero.

Figure 6 illustrates the response of the Twin Lakes snow pillow to the temperatures in the surrounding area. First melt at the snow pillow occurred on or about March 16, after only one day when the maximum temperature at Slave Lake rose about 0°C (figure 7). Between that date and March 24, approximately 8 mm of melt was generated (a rate of 1 mm/day) after only 17 C°-days of melting with mean daily temperatures in the order of 2°C. After March 24, the melt accelerated and by about March 31, the last of the remaining 42 mm of melt was completed. This was achieved at a rate of 6 mm/day at mean daily temperatures still less than 5°C, but with daily maximums in the order of 10°C. On the whole, it took 40 C°-days of heating over a period of 16 days to melt the entire snow pack.

The gauge on the Little Paddle River at Mayerthorpe (WSC Gauge #07BB005) showed diurnal fluctuations as early as March 27, more than one half of the way through the snow melt period. These fluctuations continued with a daily variation of about 0.10 m until April 12 (figure 8) when open water conditions became apparent. There was no stage increase associated with breakup, with a mean daily stage of only 0.6 - 0.7 m evident throughout. Observations on March 29 indicated that the Little Paddle River was completely clear of ice near its confluence with the Paddle River (figure 9).

As expected, the Paddle River took slightly longer to respond to the melt even though releases from the partially completed dam at Rochefort Bridge may have affected the ice regime upstream of Barrhead. As of March 29, the ice cover upstream of the dam was still intact (figure 10) but some open leads had developed. The forebay of the dam

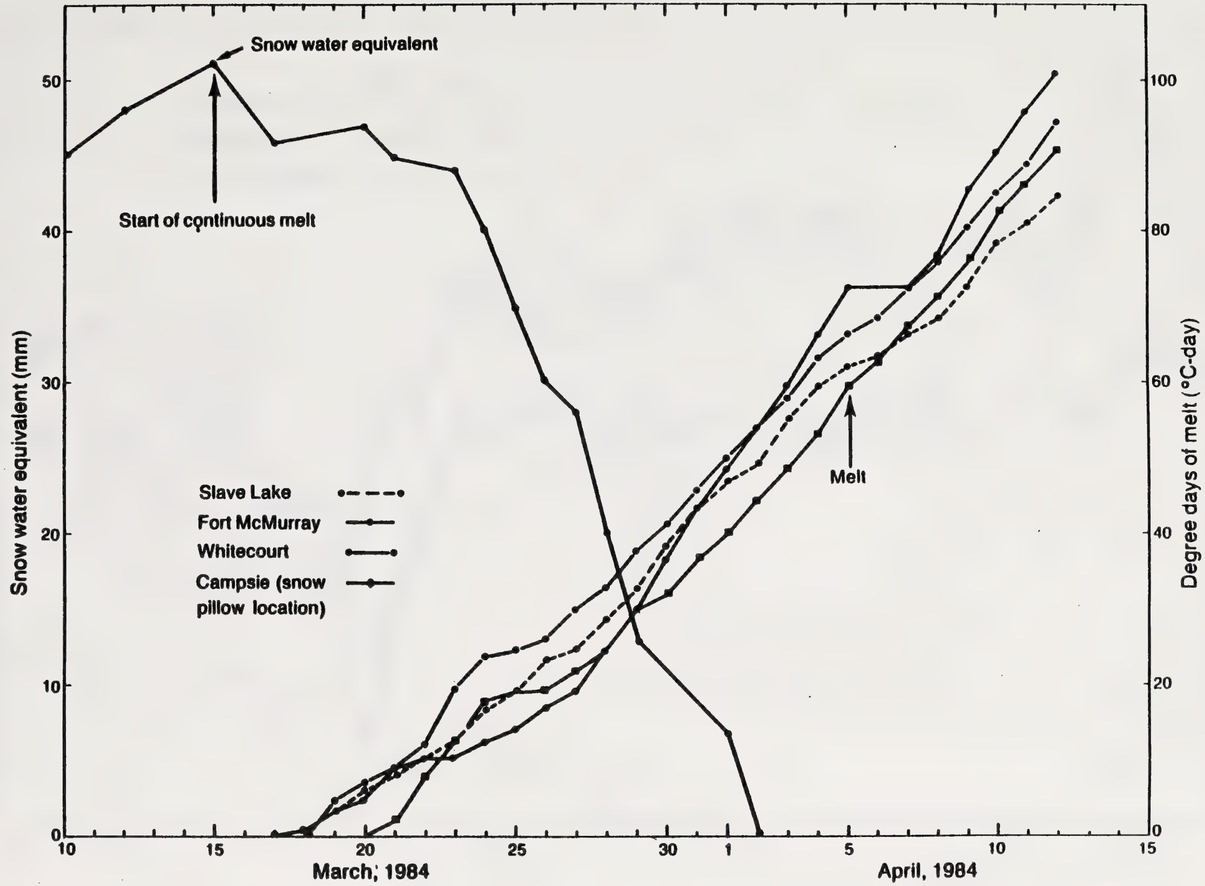

Figure 6. Degree days of melting and snow pack reduction at the Twin Lakes snow pillow, Spring 1984

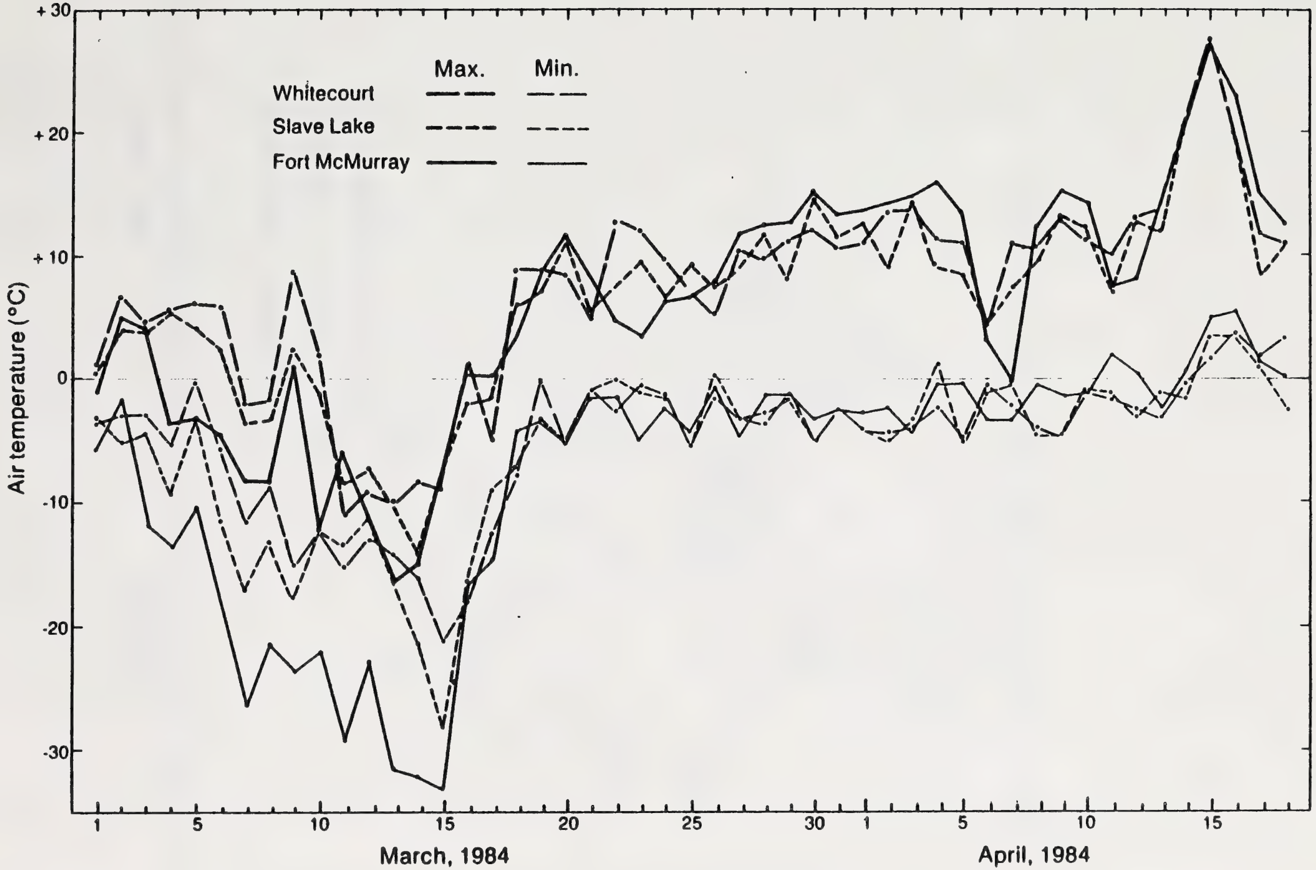

Figure 7. Daily air temperatures in the Athabasca River basin, Spring 1984

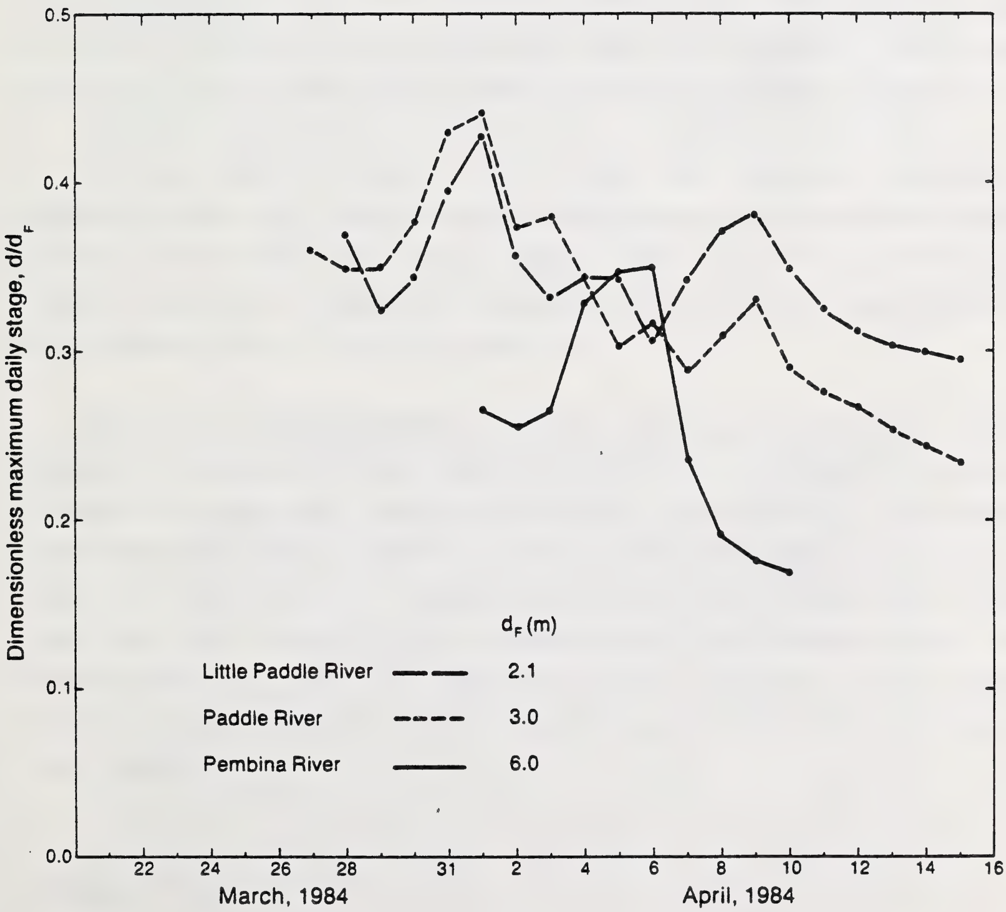

Figure 8. Dimensionless gauge heights on the Little Paddle, Paddle, and Pembina Rivers during the 1984 breakup

was ice covered but it appeared that releases of warm water from the dam had melted the ice cover downstream to within 8 km of Barrhead. This type of thermal breakup probably did not produce high water levels. Downstream of Barrhead, the cover was intact (figure 11) all the way to the Pembina River, although open leads appeared along the edges and some locally broken ice accumulated against the intact Pembina River ice.

The head of the cover reached Barrhead on March 31 but ice effects persisted until April 9. A peak stage of 1.32 m, about 0.3 m above the mean pre-breakup level, resulted during that period. Following the peak on April 1, the water level declined slowly to a stage of 0.68 m which was more or less maintained for the duration of the month (figure 8).

On the Pembina River, a solid cover was observed upstream of Sangudo on March 29. Most of the snow had melted and surface melting of the ice cover itself was taking place. The ice cover was intact and looked competent at Rossington, Jarvie, and all the way downstream to the Athabasca River (figures 12 and 13).

At the WSC Gauge #07BC002 at Jarvie, the pre-breakup stage varied between 1.5 and 1.6 m from March 30 to April 3. On April 4, a 0.5 m increase in stage over a period of two days (until April 6) resulted in the removal of the ice cover and subsequently the stage was reduced to about 1.00 m by April 10. Observations on April 10 showed that the ice cover had been removed as far downstream as the Athabasca River. No observations were available upstream of the confluence of the Paddle River to indicate whether or not the ice cover was still in place in these reaches.

Athabasca River

Observations of ice conditions on the Athabasca River were first made on March 29. The ice cover was generally intact from a point upstream of the mouth of the Pembina River (figure 14) past Hondo

Figure 9. Open water on the Little Paddle River near its confluence with Paddle River, March 29, 1984

Figure 10. Intact ice cover on the Paddle River upstream of the Paddle River Dam, March 29, 1984

Figure 11. Solid ice cover on the Paddle River downstream of Barrhead, March 29, 1984

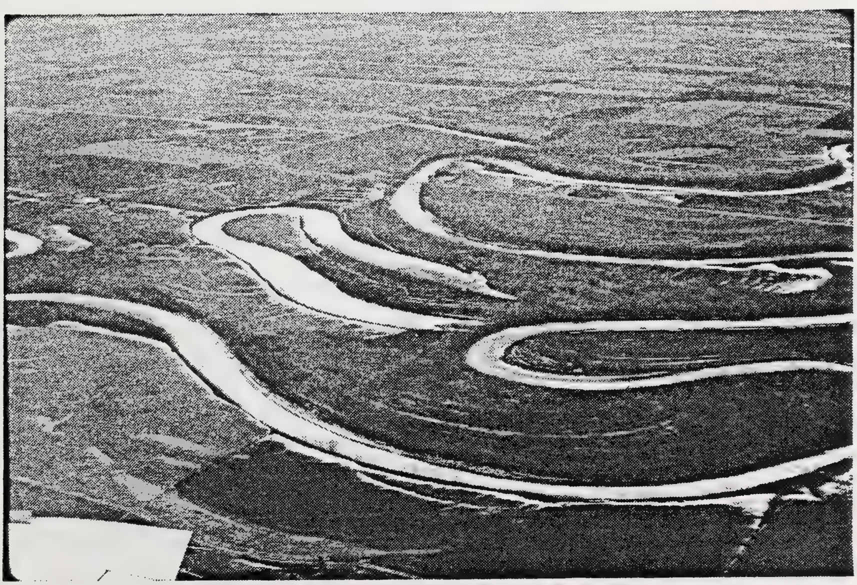

Figure 12. Intact ice cover on the Pembina River at Rossington, March 29, 1984

(figure 15) and downstream to Smith. Some open leads were evident around gravel bars and near the banks. At Smith, the Lesser Slave River was ice free and had produced an open lead approximately 20 channel widths long and 0.2 channel widths wide along the left bank of the Athabasca River. Between Smith and the Town of Athabasca, the ice cover appeared to be very competent with only a minimal amount of surface deterioration.

At the Town of Athabasca (figure 16) both Muskeg Creek and the Tawatinaw River had broken up, causing only limited effects on the Athabasca River ice. An essentially solid and competent ice cover was observed from the Town of Athabasca downstream past the mouth of the Calling River (km 610) (which was still ice covered) to Iron Point (km 558), where mid-channel leads were first evident (figure 17). Downstream from there, the cover was intact except for open leads at (km 474) and Grande Rapids (km 427) (figure 18). Immediately downstream of Grande Rapids there was open water extending downstream for about 5 channel widths, as was observed in previous years.

Between Grande Rapids and Crooked Rapids (km 334) the cover was intact except for the odd open lead particularly noticeable downstream of Brule Point (km 396) and at Boiler Rapids (km 354) (figure 19). Both Crooked Rapids (figure 20) and Mountain Rapids (km 306) showed evidence of melting and surface overflow. Downstream of Mountain Rapids, past the confluence of the Clearwater River (figure 21) to the Suncor plant (km 264), the cover was intact with virtually no snow cover and almost no deterioration of the ice cover. Downstream of the Suncor plant, the warmer effluents had deteriorated the ice cover substantially and an open lead had formed for a considerable distance downstream along the left bank (figure 22).

Landsat imagery on April 1 (figure 23) indicated similar conditions. The ice cover on the Athabasca River was intact from Whitecourt downstream to the mouth of the Lesser Slave River, except for two distinct reaches. A 10 kilometre long reach downstream of Vega Ferry and a 3 kilometre long reach located 10 kilometres upstream of the

Figure 13. Intact ice cover on the Pembina River at its confluence with the Athabasca River, March 29, 1984

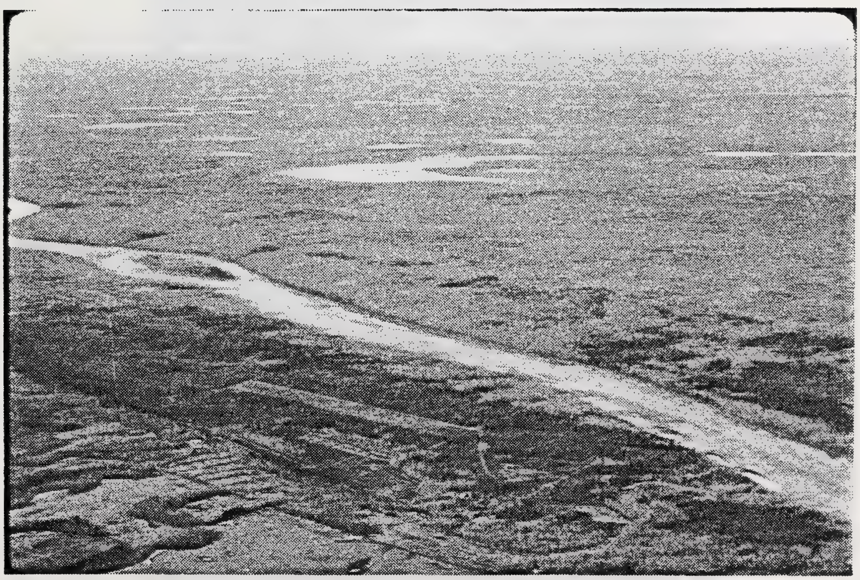

Figure 14. Intact but deteriorating ice cover on the Athabasca River upstream of the Pembina River, March 29, 1984

Figure 15. Solid ice cover on the Athabasca River at Hondo (km 806), March 29, 1984

Figure 16. Intact ice cover on the Athabasca River at the Town of Athabasca, March 29, 1984

Figure 17. Open leads developing on the Athabasca River at Iron Point (km 558), March 29, 1984

Figure 18. Open leads at Grande Rapids (km 427) on the Athabasca River, March 29, 1984

Figure 19. Minimal amounts of deterioration through Boiler Rapids (km 354) on the Athabasca River, March 29, 1984

Figure 20. Open leads and overflow at Crooked Rapids (km 334) on the Athabasca River, March 29, 1984

Figure 21. Solid ice cover on the Athabasca River at the mouth of the Clearwater River (km 293), March 29, 1984

Figure 22. Open water along the left bank of the Athabasca River in the vicinity of Suncor (km 264), March 29, 1984

Figure 23a. Landsat imagery of the Athabasca River, showing areas of open water, April 1, 1984

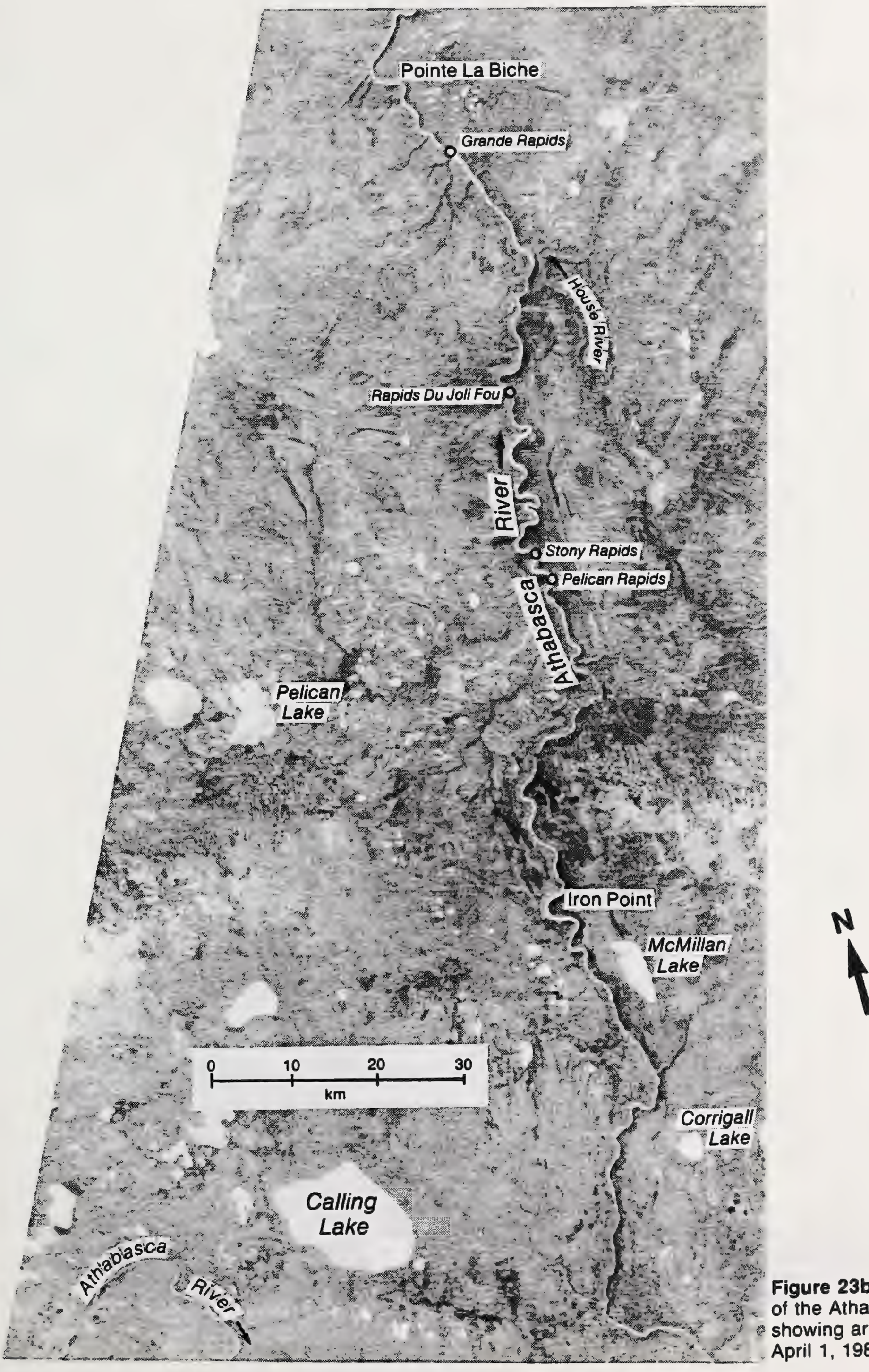

Figure 23b. Landsat image of the Athabasca River, showing areas of open wate[r] April 1, 1984

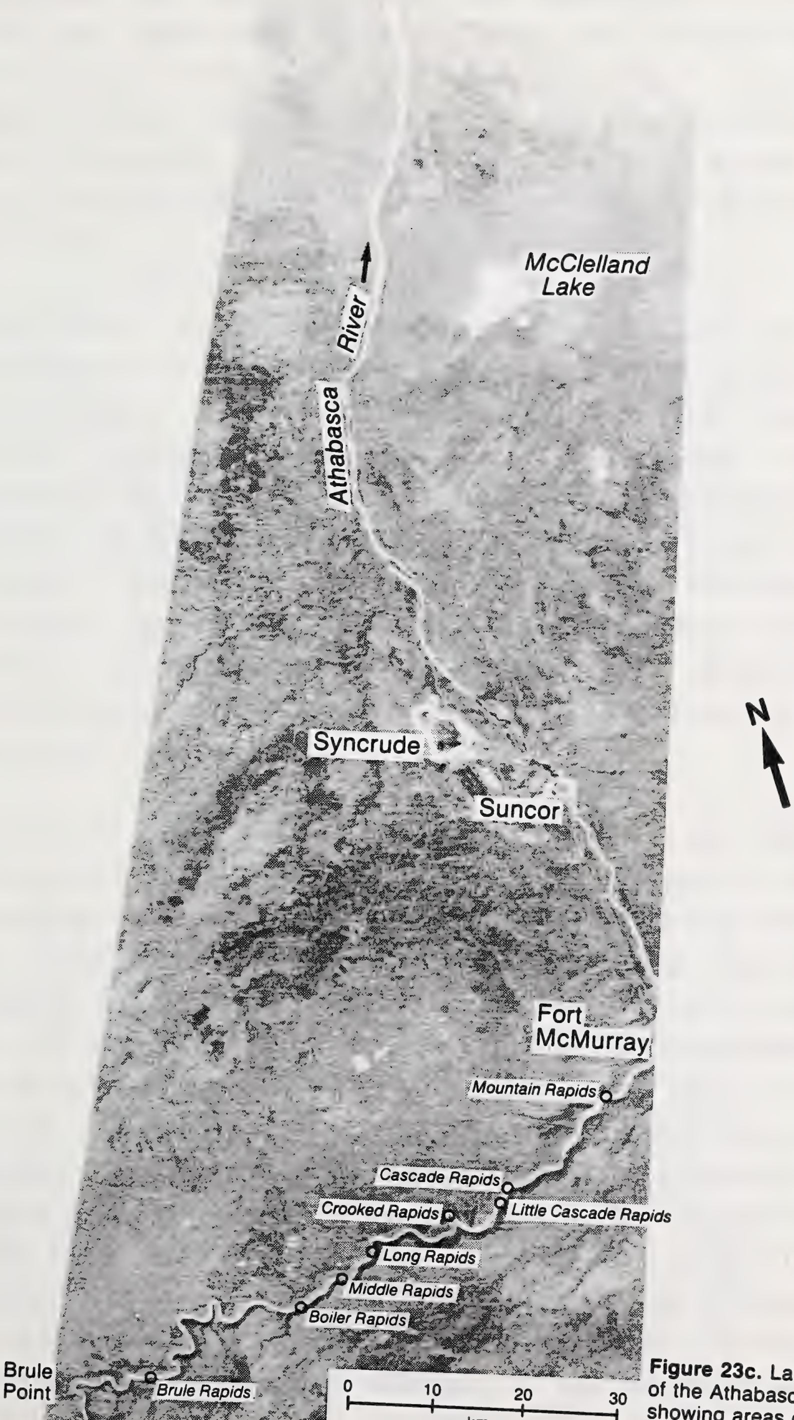

Figure 23c. Landsat imagery of the Athabasca River, showing areas of open water, April 1, 1984

Pembina River were both completely open. The Lesser Slave River was obviously ice free. Downstream of its confluence, the Athabasca River was essentially ice covered except for some open leads. From the Landsat imagery, the most obvious of these leads were located downstream of the Lesser Slave River, within Grande Rapids, in Boiler Rapids, in the vicinity of the Syncrude pipeline crossing (km 329), and downstream of the Suncor plant.

Additional aerial reconnaissance on April 7 showed that the ice cover on the Athabasca River was intact, but approximately 80 percent of it had melted in place. This indicates that there was no stage increase to move the cover and break it mechanically. Instead, thermal forces were doing most of the damage (figure 24). Ice cover characteristics typical in figure 24 existed from the mouth of the Pembina River to the Town of Athabasca (figure 25). Downstream of Athabasca, to the mouth of the Calling River, considerably less open water was observed but the cover appeared to be deteriorating rapidly (figure 26). Observation downstream of the mouth of the Calling River had to be discontinued due to poor visibility.

Water Survey of Canada records at gauge (#07BE001) at the Town of Athabasca indicate that the first significant rapid increase in stage associated with ice movement occurred as early as 12:00 hours on April 7 (figure 27). This was preceded by a gradual rise in stage from about 1.1 m on March 20 to 1.55 m on April 5 and a further increase in stage of 0.3 m to 1.80 m on April 6. The peak stage of 2.5 m occurred at 18:00 hours on April 7 and probably resulted from a very small ice run past the gauge. Another peak of 2.5 m occurred at 14:00 hours on April 8 probably due to another run. From the stage records it is apparent that breakup was very mild and uneventful. This is borne out by figure 28, taken on April 12 (5 days after breakup), which illustrates the very low shear walls and the large amounts of ice left behind as only the centre portion of the channel was freed of ice. The source of the ice which generated the stage increases at the Town of Athabasca was undoubtedly the very weakened and deteriorated ice observed on April 7 upstream of the town.

Figure 24. An almost completely deteriorated ice cover on the Athabasca River upstream of the Town of Athabasca, April 7, 1984

Figure 25. Deteriorating ice cover on the Athabasca River at the Town of Athabasca, April 7, 1984

Figure 26. Intact, but deteriorating ice cover on the Athabasca River downstream of the mouth of the Calling River (km 610), April 7, 1984

Landsat imagery on April 9 shows that the breakup process had advanced considerably since the last reconnaissance. Although the ice cover was still intact between Whitecourt and Fort Assiniboine the channel was completely clear of ice between the former location and Hondo (figure 29a, b) and a 3 kilometre long jam appeared to have formed at Rourke Creek. Downstream of Hondo, the channel was once again clear of ice as far as the mouth of the La Biche River where either the head of running ice or an ice jam was positioned. This mass of ice extended downstream to the mouth of Calling River, below which the channel was intermittently ice covered and the ice seemed to be melting in place. At Pelican Rapids the ice cover once again became continuous as far downstream as Long Rapids. This solid cover was punctuated by a 10 kilometre open section at the House River confluence and shorter open stretches in the vicinity of the numerous rapids.

Landsat imagery on April 10 at approximately 08:30 hours confirms the previous days imagery upstream of the Town of Athabasca. In addition, all the intermittent ice observed between the mouth of the Calling

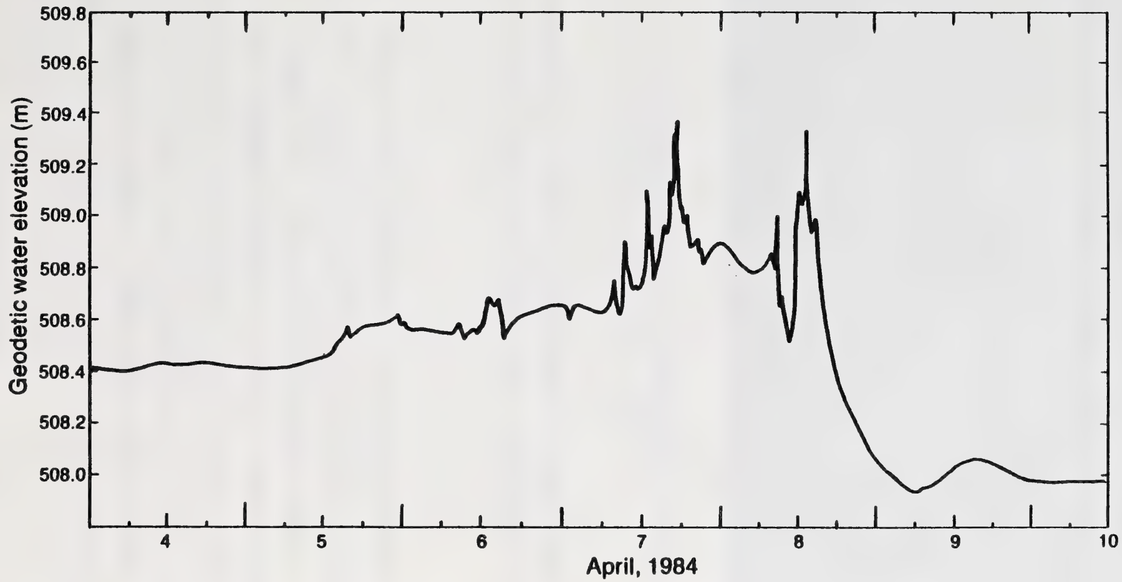

Figure 27. Water levels during breakup on the Athabasca River at WSC Gauge #07BE001 at the Town of Athabasca

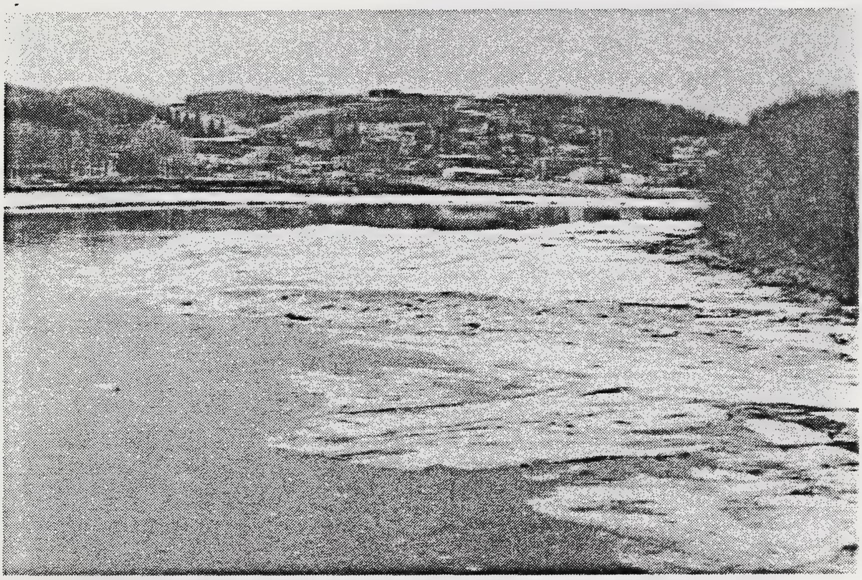

Figure 28. Remnants of breakup on the Athabasca River at the Town of Athabasca, April 12, 1984

River and Pelican Rapids on April 9 had moved downstream and filled up the channel between the mouth of the House River and Pelican Rapids (figure 29c, d).

Downstream of Brule Point, the river is open continuously as far as Middle Rapids (km 350) where the solid white cover probably indicates the presence of a jam with a toe located downstream of Long Rapids (km 345). This would suggest that the jam is about 8 km long, at a maximum. Downstream of this jam the ice cover becomes intermittent with open water evident at Crooked Rapids, upstream of Little Cascade Rapids (km 327), and at Mountain Rapids. Downstream from there, the cover is intact, except for a 20 km length downstream of the Suncor plant.

By 17:00 hours on April 10, at which time the first helicopter reconnaissance was undertaken, the situation downstream of Grande Rapids

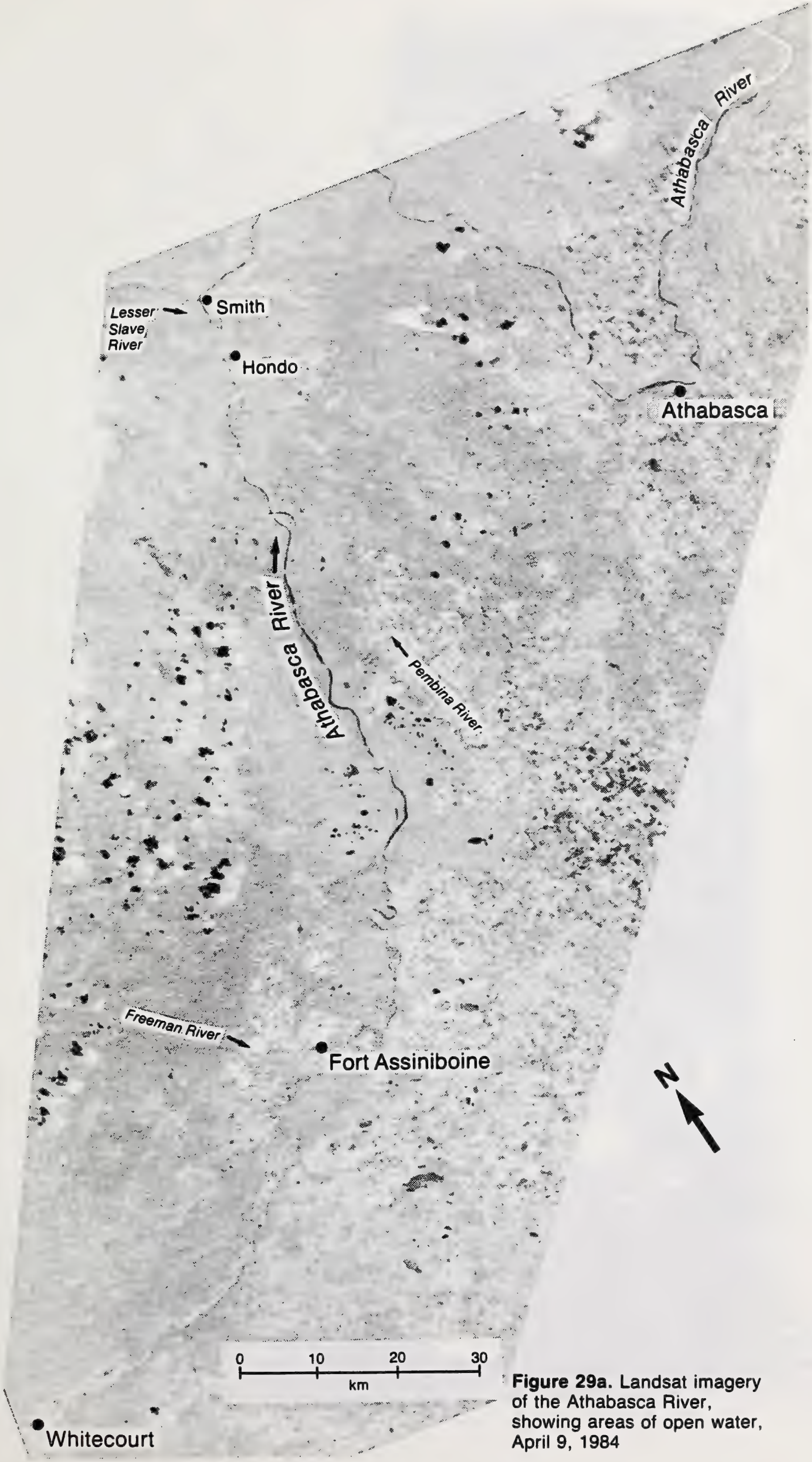

Figure 29a. Landsat imagery of the Athabasca River, showing areas of open water, April 9, 1984

Figure 29b. Landsat imagery of the Athabasca River, showing areas of open water, April 9, 1984

Figure 29c. Landsat imagery of the Athabasca River, showing areas of open water, April 10, 1984

Figure 29d. Landsat imagery of the Athabasca River, showing areas of open water, April 10, 1984

had change considerably. A light ice run, originating from downstream of Pelican Rapids was observed. Evidently, the jam located upstream of the mouth of the House River (apparent in the Landsat imagery taken earlier in the day) had released and forced the ice cover to move downstream. This ice run was observed to be continuous to Point La Biche (figure 30), downstream past Brule Point, where 2-3 m shear walls were evident from the previous ice run (figure 31), all the way to Middle Rapids (km 350) where the intact cover was observed at 17:50 hours (figure 32). By 18:00 hours the broken ice had advanced past Long Rapids (km 345) and by 19:00 hours the ice run reached Rock Rapids (km 330). This indicates celerities of 8 m/s and 4 m/s, respectively.

The water level at the WSC gauge downstream of Fort McMurray was relatively constant during the time prior to April 10. On that day, at 05:00 hours there was a gradual rise in the water level of about 0.12 m over a four hour period (figure 33). This indicates that a surge of water of unknown origin had passed by, because in another five hours the gauge had dropped back to normal. At 16:00 hours there was a slight drop in the gauge height probably due to storage of flow upstream, although the drop is so small (less than 0.02 m) it could be due to the usual diurnal fluctuations superimposed on the surge.

Following the observation of the toe of the moving ice at Rock Rapids at 19:00 hours, the run continued downstream at a celerity of 2.6 m/s until it jammed just below the mouth of the House River at 22:40 hours. This caused the stage to drop by 0.2 m at MacEwan Bridge (figure 34) but did not seem to affect the stage of the WSC gauge. The jam remained in this position for about two hours, building up approximately 6 m of head in the region of the toe. The jam subsequently released at 00:26 hours on April 11, caused a 2.2 m increase in stage up to 244.5 m at MacEwan Bridge at 00:30 hours, and a stage increase of 2.5 m up to an elevation of 241.0 m at the WSC gauge at about 02:00 hours. Subsequent measurements at the mouth of the Clearwater River showed the stage increase at that location to be approximately 2.8 m above the pre-breakup water level.

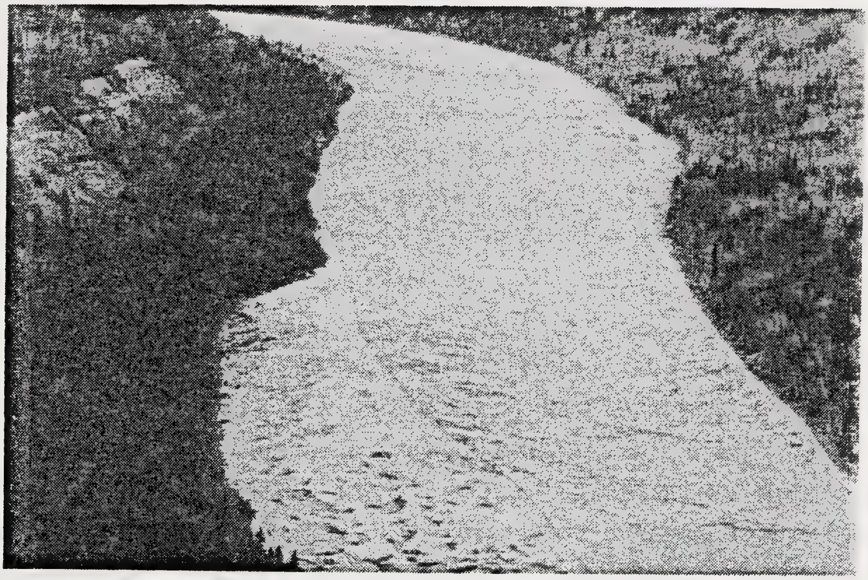

Figure 30. Ice run on the Athabasca River at Point La Biche (km 411), 17:00 hours, April 10, 1984

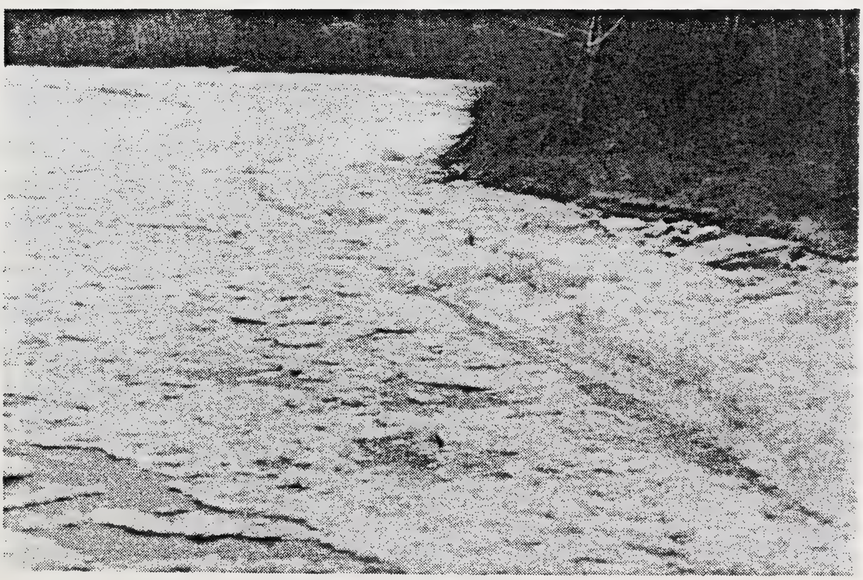

Figure 31. Shear walls from a previous ice run on the Athabasca River at Brule Point (km 396), 17:00 hours, April 10, 1984

Figure 35 illustrates the stage variation at MacEwan Bridge and the WSC gauge during the ice run. It took about one hour for the toe to travel the distance of 5 km between the bridge and the gauge. This results in a celerity of only 1.4 m/s, considerably less than measured upstream. Also, it is apparent that the peak stage increases as the jam moved downstream. This is most probably due to the reduction in channel slope and the constant ice supply provided by the competent ice still located within the channel between the two locations.

During the ice run past the WSC gauge, the peak stage occurred slightly after 02:00 hours and the run was observed to have reached Suncor by at least 03:00 hours. The high stage at the WSC gauge continued for about seven hours until 08:00 hours, at which time the stage had dropped by 1.6 m. Following this minimum stage, the gauge level increased to 4.75 m over a period of nine hours. Apparently a jam had formed downstream of the gauge. This jam remained in place for about 42 hours at a gauge height in the order of 4.6 to 4.8 m and then the stage slowly decreased to a gauge height of about 2.0 m on April 17 (a rate of 0.65 m/day).

Following the observations of breakup at Fort McMurray, a quick reconnaissance was made of the ice conditions on the Athabasca River in the upstream parts of the basin. As of April 12, about eight days after breakup on the Pembina River and four days after breakup at the Town of Athabasca, the ice cover at Fort Assiniboine, Blue Ridge, and Whitecourt was essentially still in place. This condition existed even though there was about 90 C°-days of melting at Whitecourt and the ice on the McLeod River had gone out (figure 36). Obviously, the lack of a significant ice run on the McLeod River, as evident in figure 36, prevented the ice on the Athabasca River from being driven out. The result was a very solid-looking cover with only border melt evident at Blue Ridge (figure 37) and competent ice at Fort Assiniboine (figure 38).

Figure 32. Toe of running ice impinging against the intact ice cover on the Athabasca River at Middle Rapids (km 350), 17:50 hours, April 10, 1984

Clearwater River

As in most previous years the breakup on the Clearwater-Christina River system lagged behind that of the Athabasca River. Observations on April 11 indicated that the ice cover in the Christina River was intact due to the low runoff generated in the basin but considerable thermal deterioration had occurred (figure 39). The Clearwater River, on the other hand, was much more active and considerable open water was evident upstream of the mouth of the Christina River (figure 40) although at WSC Gauge #07CD001 at Draper, the majority of the flow was over the ice (figure 41). Gauge records, although discontinuous due to the malfunction of the gauging system, indicate that a significant increase in stage occurred at about 17:00 hours on April 12. It is not known whether this resulted from breakup on the Christina River or from incoming ice from the upper reaches of the Clearwater River.

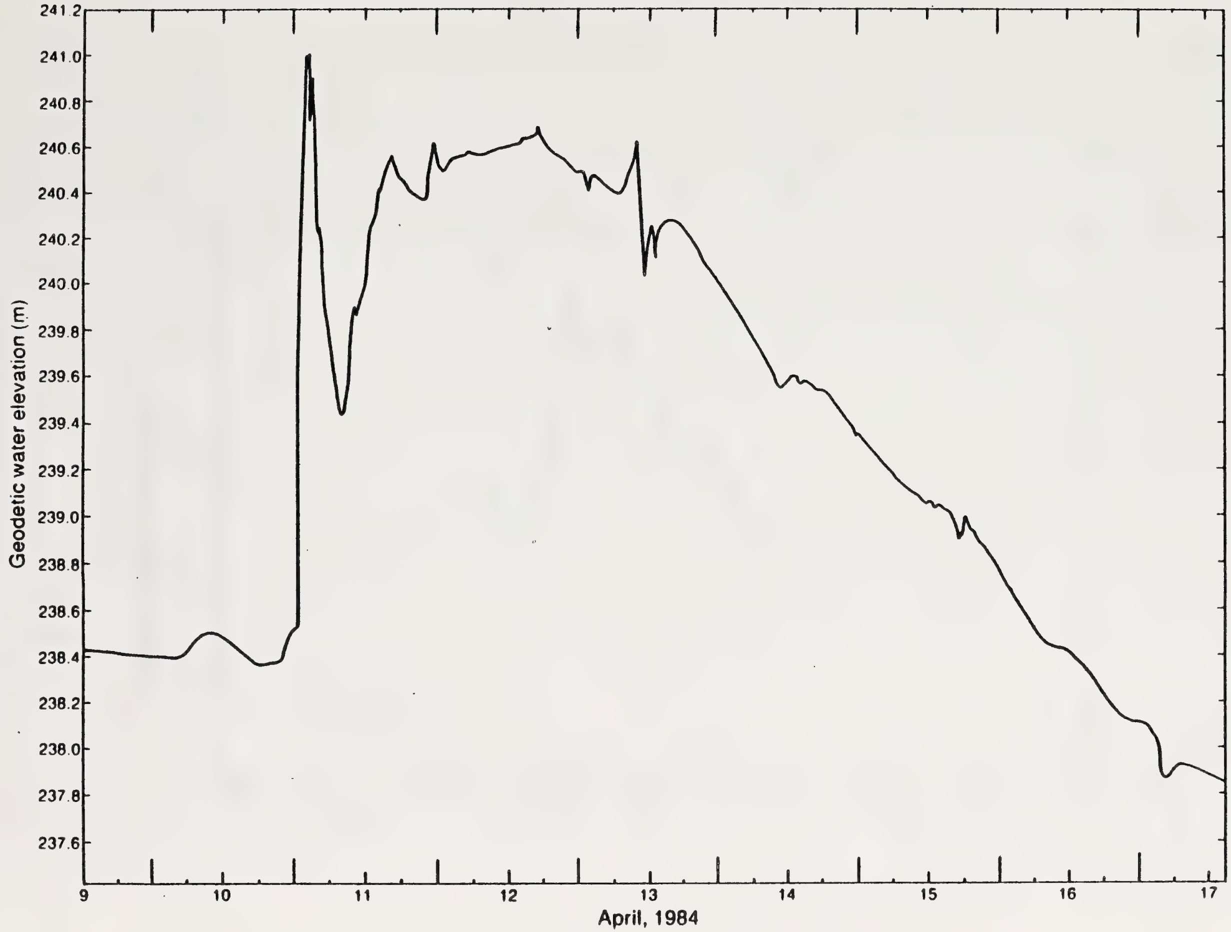

Figure 33. Water levels during breakup on the Athabasca River at WSC Guage #07DA001 downstream of Fort McMurray

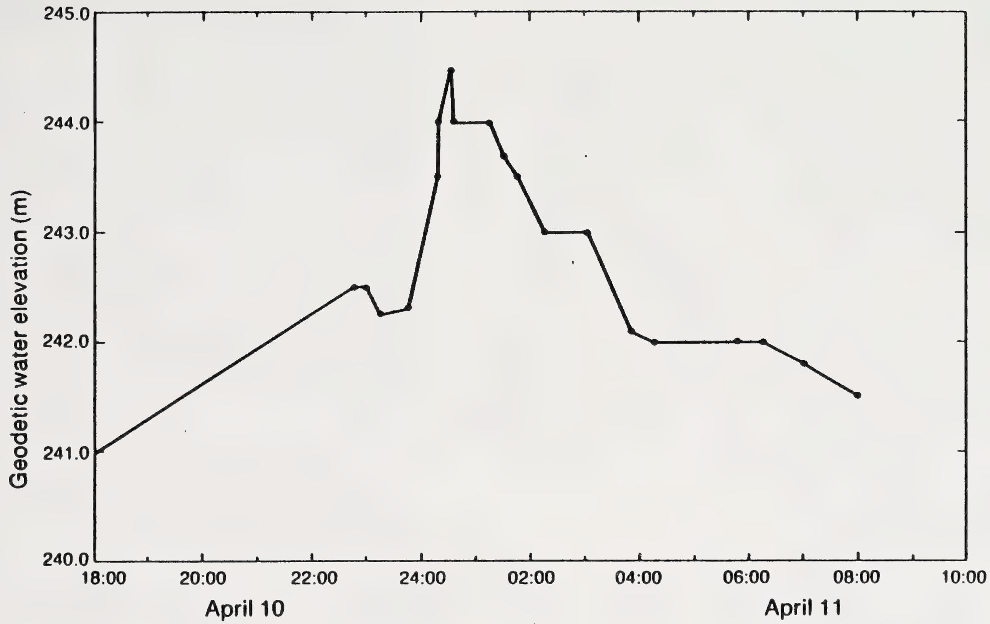

Figure 34. Observed water levels at MacEwan Bridge (km 295) on the Athabasca River at Fort McMurray, April, 1984

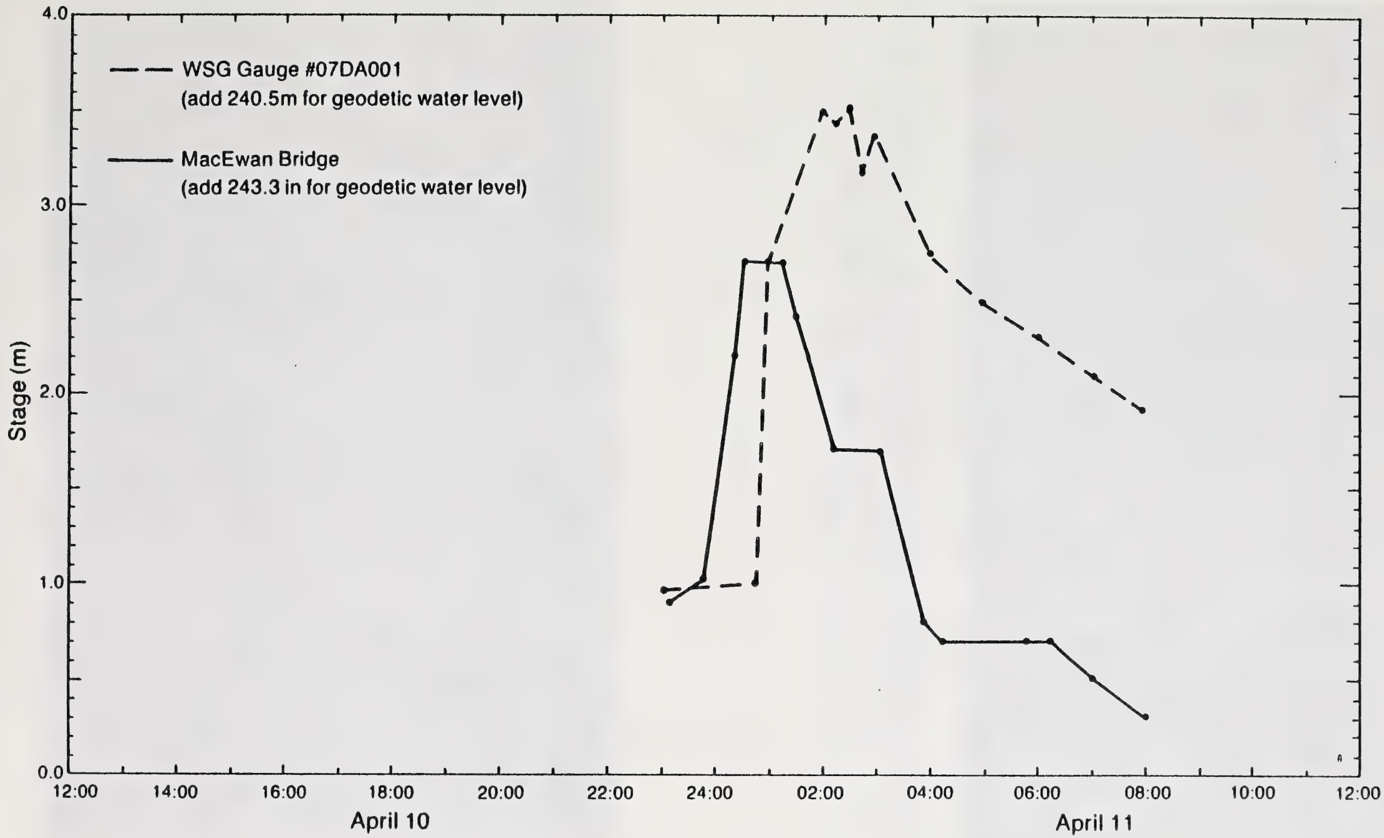

Figure 35. Stage fluctuations at MacEwan Bridge and at WSC Gauge #07DA001 during the passage of the surge following the failure of the ice jam, April, 1984

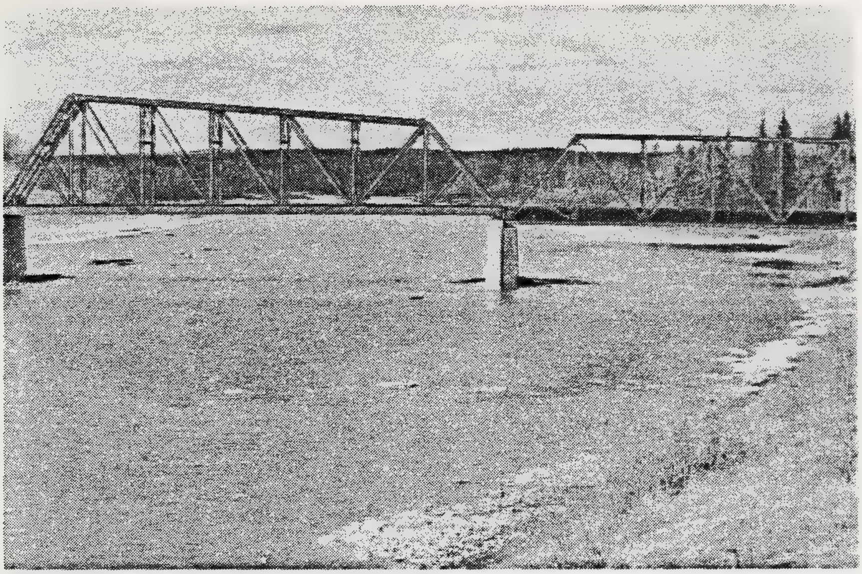

Figure 36. Open water on the McLeod River at Whitecourt with only scattered evidence of what appears to be a very low ice run, April 12, 1984

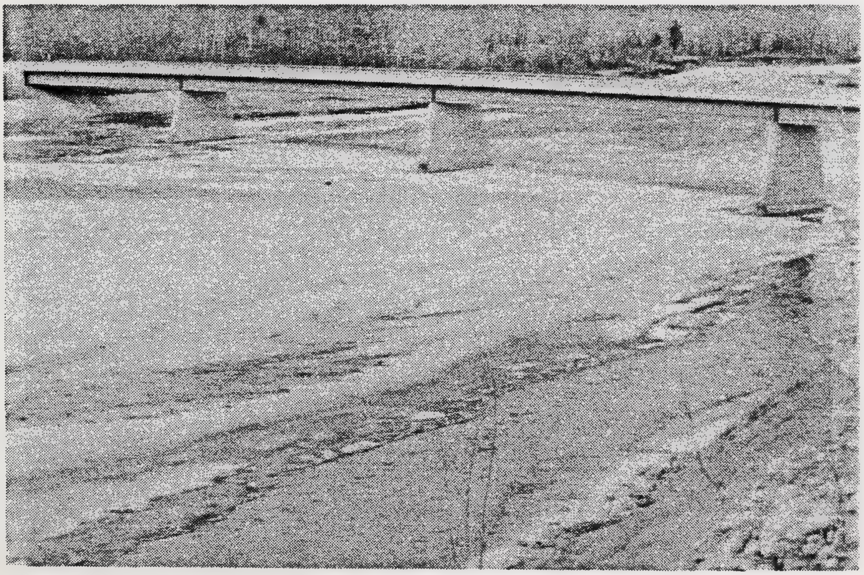

Figure 37. Solid ice cover with border melt on the Athabasca River at Blue Ridge, April 12, 1984

Figure 38. Solid ice cover with a mid-channel lead in the background on the Athabasca River at Fort Assiniboine, April 12, 1984

Figure 39. Deteriorating ice cover on the Christina River approximately 8 km upstream of the Clearwater River, April 11, 1984

Figure 40. Open water on the Clearwater River at the mouth of the Christina River, April 11, 1984

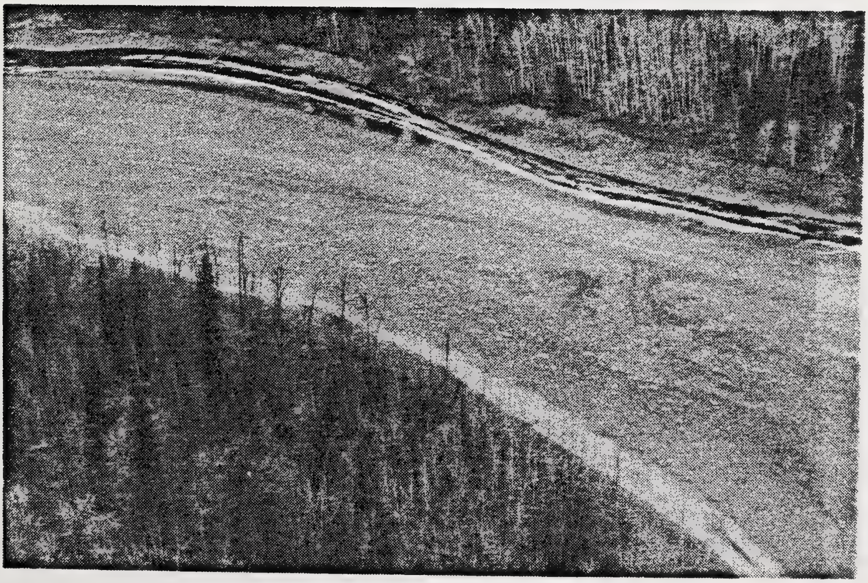

Figure 41. Flow on the surface of the ice cover at WSC Gauge #07CD001 on the Clearwater River at Draper

ANALYSIS OF THE MOBERLY RAPIDS JAM

A complete documentation of the Moberly Rapids jam during its stable period could not be made because of darkness. However, it was possible to ascertain the time during which the ice jam stabilized, the location of the toe, and other pertinent features accessible without using aircraft. Most of the relevant information necessary for the stability analysis of the jam was collected at first light on the following day (April 11). This information included the maximum ice levels associated with jam and the thicknesses of the exposed shear walls. These not only give an indication of the thickness of the jam but also the location of its head.

The ice jam levels were determined in three ways. In the vicinity of the toe and downstream of the Suncor pipeline crossing, the maximum ice level was determined by levels run from established benchmarks and by the heights of the shear walls. Upstream of the Suncor pipeline crossing, the maximum ice jam levels were determined photographically using the gauges established for that purpose (Andres and Rickert, 1984).

The thicknesses of the shear walls were all measured photographically and their heights were measured relative to the water levels occurring at the time of the documentation. It is therefore important to note that the following reported ice jam thicknesses are most likely the minimum values. Nevertheless, they provide valuable clues to the range of thicknesses one might expect.

Physical Characteristics

Figure 42 illustrates the aerial extent of the Moberly Rapids jam. The toe of the jam was located at km 295.7, about 0.8 km upstream of MacEwan Bridge. The overall length of the jam was 9.4 km with the head located at approximately km 306, just downstream of Mountain Rapids.

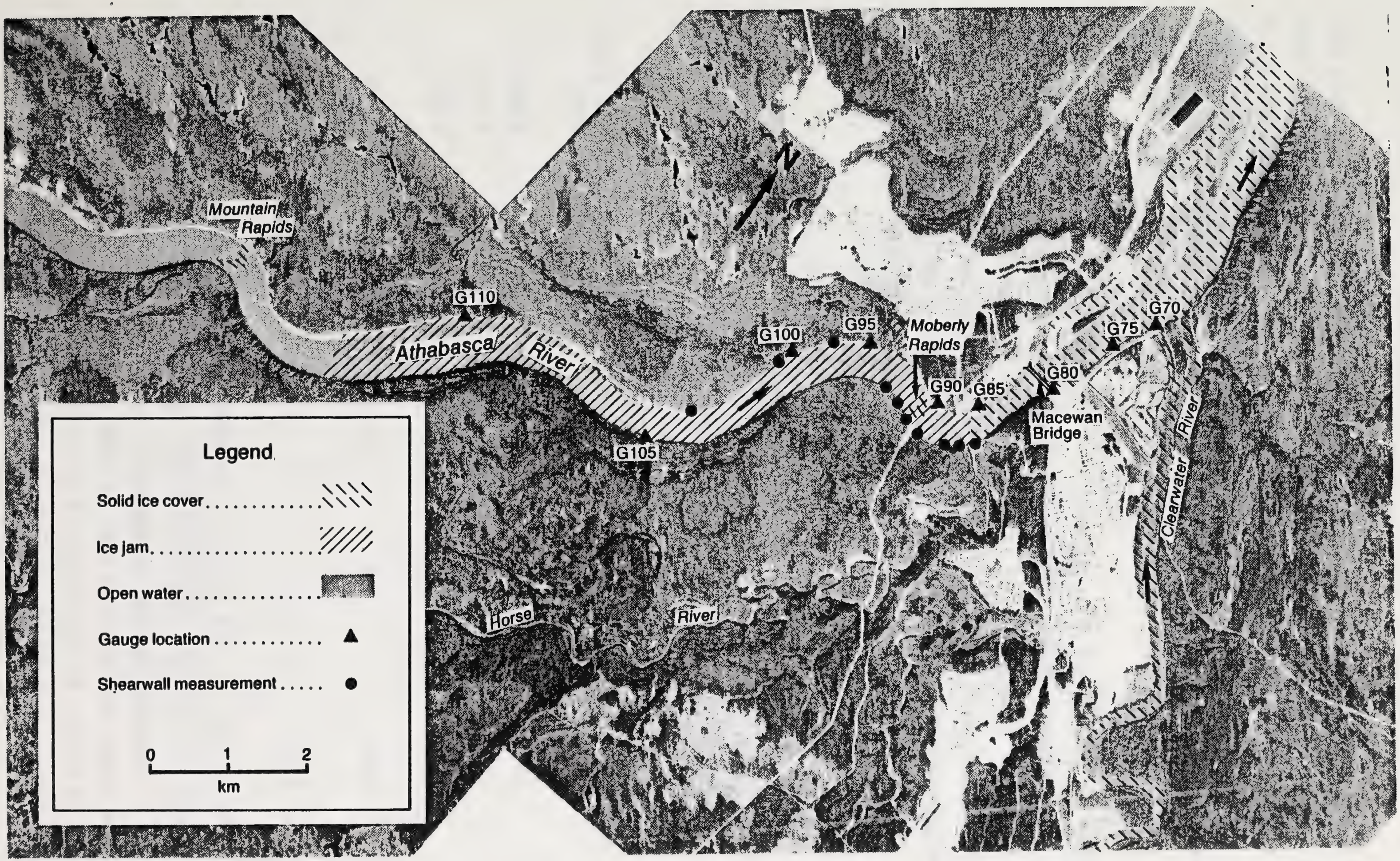

Figure 42. Extent of the Moberly Rapids jam, April 10, 1984

The slope of the section of the jam between the toe and the start of the equilibrium portion of the jam at km 300.0 (Moberly Rapids) was about 5.0 m/km (figure 43). The equilibrium portion of the jam (the only part amenable to a simple analysis) extended upstream from km 300.0 to km 303.4, a distance of 3.4 km. The slope of this portion of the jam averaged about 0.8 m/km and was very close to the open water slope.

The geometric characteristics of the jam are summarized in table 4. These data are based on four available cross-sections within the equilibrium portion of the jam (figure 44). It is evident that the mean height of the jam, which include both ice and water is 6.5 m. Although this is a significant event, it cannot compare to the observed jams in 1977 and 1978 when mean heights of 8.4 and 8.8 m respectively were measured.

Table 4.
Summary of Geometric Characteristics of the Moberly Rapids Jam

Cross Section (km)	Bed Elevation (m)	Bed Elevation (m)	Mean Height H (m)	Channel Width W (m)
296.5	237.5	247.0	7.0	455
297.7	240.0	248.0	6.0	420
298.7	241.8	-	7.0	500
300.3	241.8	249.6	5.6	400
Mean	-	-	6.4	445

From the shear wall measurements (figure 45) it was apparent that the jam was the thickest near the downstream end of its equilibrium portion, where the shear wall thicknesses varied between 4 and 5 m (figure 43). At the upstream end of the equilibrium reach the shear wall thicknesses were estimated to be in the order of 3 to 4 m. Overall the average minimum thickness of the jam was estimated to be 4.1 m.

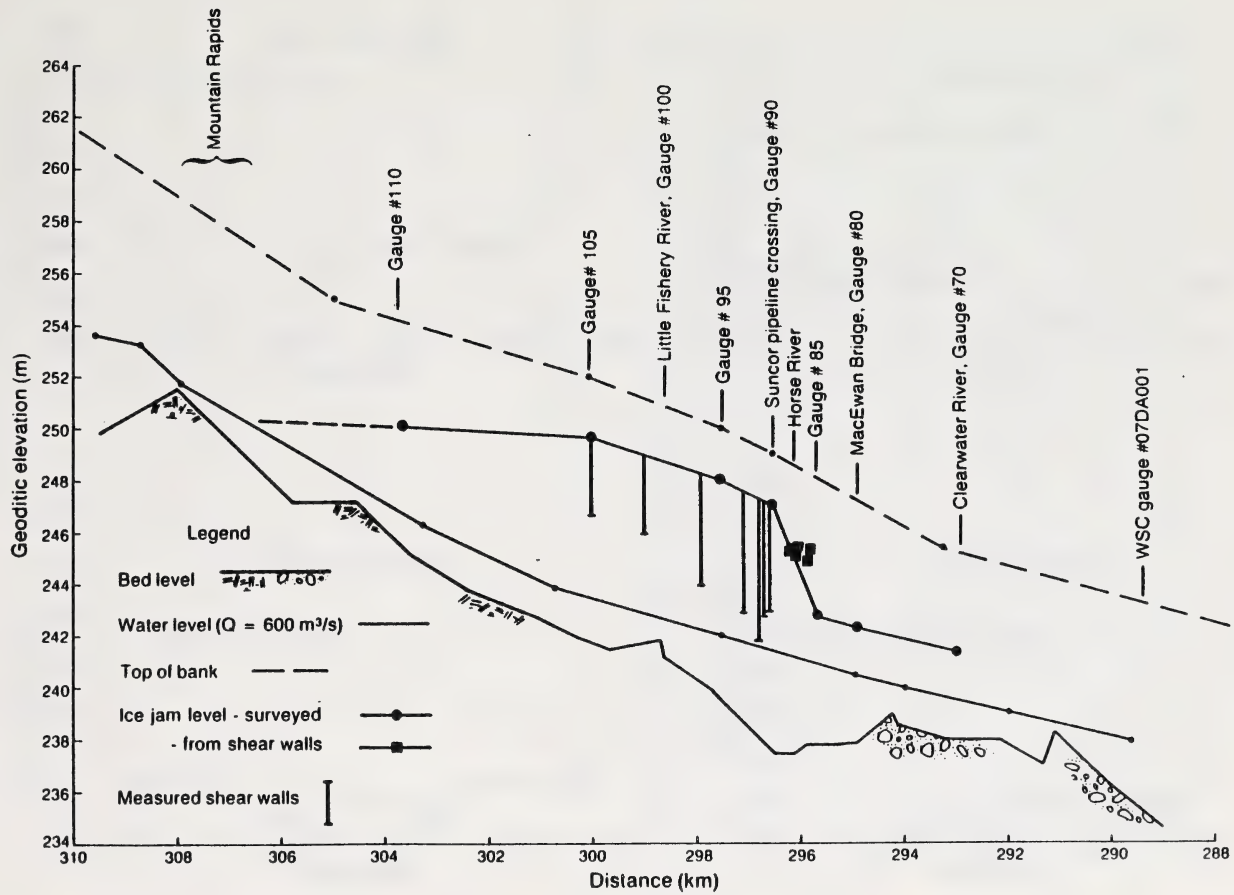

Figure 43. Ice level profile through the Moberly Rapids jam, April 11, 1984

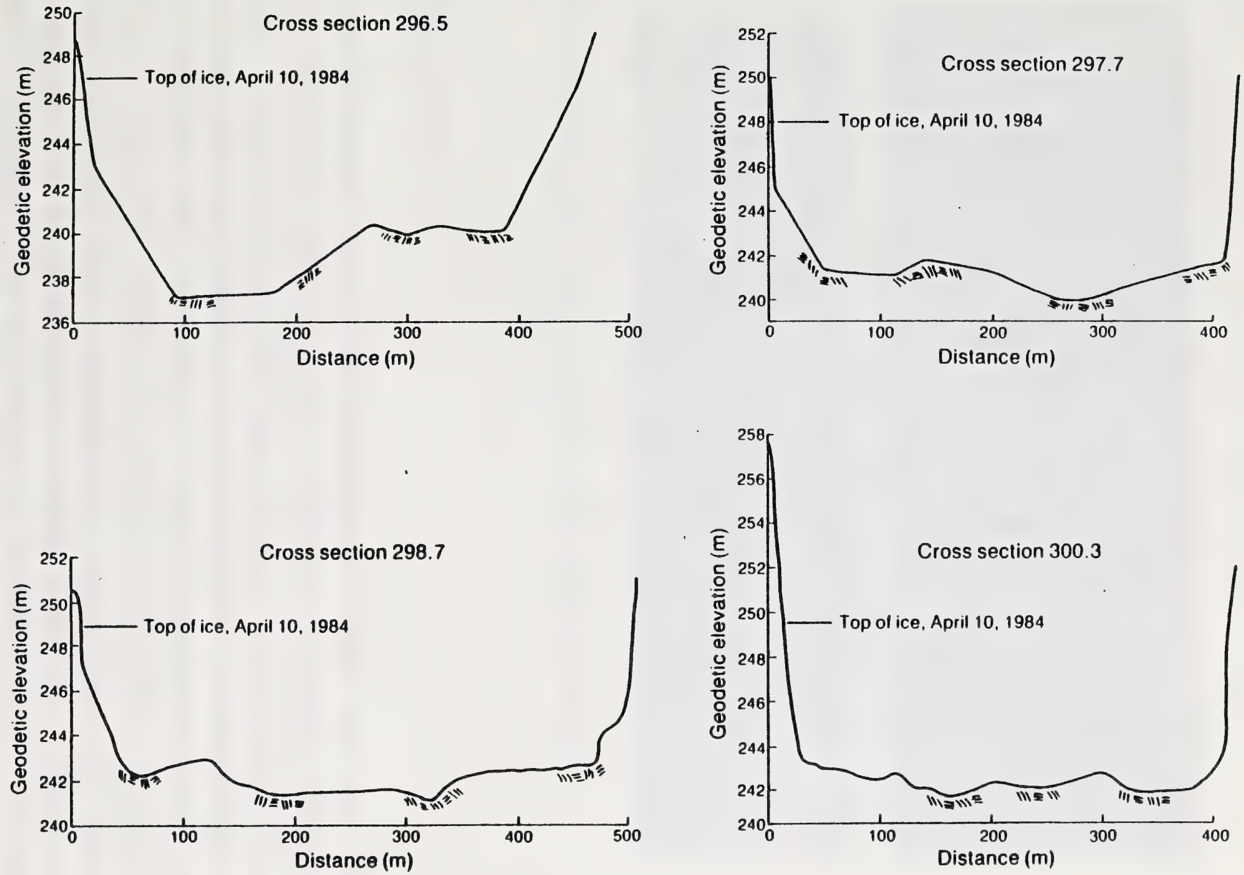

Figure 44. Surveyed cross-sections of the Moberly Rapids jam

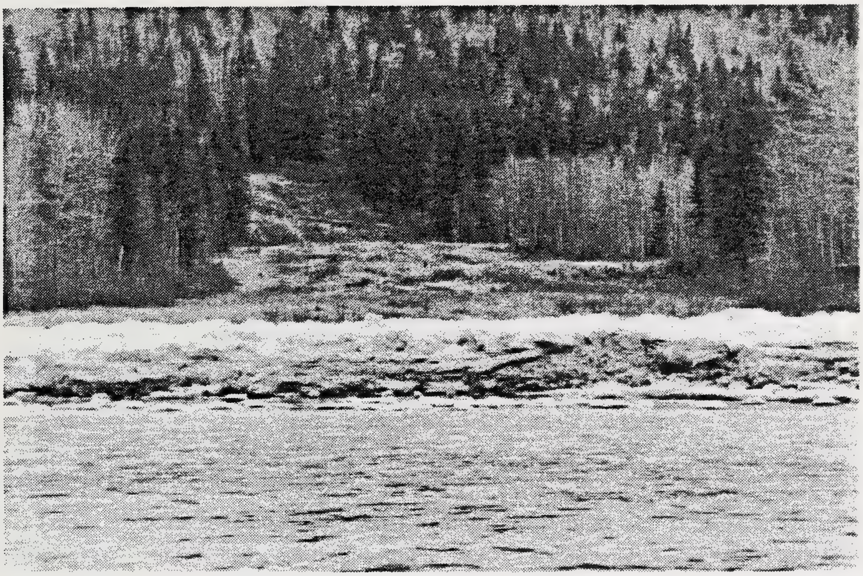

Figure 45. Shear walls resulting from the stabilization of the Moberly Rapids jam

Discharge Estimates

The discharge at which time the maximum thickness and hence maximum stage of the Moberly Rapids Jam were produced is extremely difficult to determine, even though the WSC gauge remained operational during the entire event and water levels were also recorded at MacEwan Bridge. The major reason for this difficulty is that no appropriate rating curve reflects the hydraulic conditions existing at the time. Instead, only the previous year's winter measurements, however few and distant in time, can be used to assess the hydraulic conditions. Including the changes in thickness with the changes in roughness which arise during the breakup period, makes it difficult to extrapolate from the winter measurements.

Because no other options are available, the most common method of analysis is to extrapolate the roughness and thickness of the last winter measurement forward in time until the ice cover completely disintegrates. By applying Manning's equation,

$$(1) \quad Q=(1/n_o)R_o^{2/3}AS^{1/2}$$

where Q is the discharge, A is the flow area under the cover, S is the channel slope, R_o is the hydraulic radius (equal to one half the ratio of the flow area to the top width), and n_o is the composite roughness, derived from

$$(2) \quad n_o = ((n_i^{3/2}+n_b^{3/2})/2)^{2/3}$$

where n_i and n_b are the roughness of the ice cover and channel respectively; it is possible to translate the geometric characteristics, $R_o^{2/3}A$ (which are a function of the stage and the ice thickness) into the discharge. It can be assumed, usually without significant error, that the slope is equal to the open water slope. For the Athabasca River in the vicinity of Fort McMurray, the bed roughness is relatively constant at about 0.021. The end of season ice roughness varies from year to year, but generally has values in the order of 0.020 to 0.045, resulting in composite roughness values ranging between 0.020 and 0.034.

On April 10, the day of the formation of the jam, the stage of the WSC gauge varied between 2.54 m and 2.70 m and the reported mean discharge for that day is 468 m^3/s for a mean gauge height of 2.54 m. This suggest that an overall roughness coefficient of 0.013 was applicable to the section. This appears relatively low compared to the winter measurements and must reflect either a significant decrease in the ice thickness or considerable open water at the section. Regardless, using the WSC method of analysis and a gauge height of 2.68 evident at the time of the formation of the Moberly Rapids jam (figure 33), the discharge can be computed to be 540 m^3/s.

Using a more conventional method of analysis and adopting a

composite roughness of 0.032, which is derived from the last winter discharge measurement (table 2), and an energy slope of 0.2 m/km results in a discharge of only 215 m^3/s. This seems to be very low. Even using the most optimistic roughness of 0.020 (as measured in the previous years) the discharge is only in the order of 340 m^3/s. This too appears to be very low and suggests that perhaps considerable open water existed at the gauge and one cannot assume a solid cover. Assuming the section is completely open downstream and there is negligible effect of ice, an upper limit on the discharge can be computed to be about 1050 m^3/s by using an open water slope of 0.2 m/km and a bed roughness of 0.021 (Andres and Doyle, 1984). It is evident that the possible discharge range reflected by a gauge height of 2.68 m at the WSC gauge is between 215 m^3/s and 1050 m^3/s. The actual discharge can be determined only if the ice conditions can be assessed.

Fortunately, water level measurements and ice conditions were closely monitored at MacEwan Bridge (figure 34). During the period of time when the Moberly Rapids jam was forming, the water level at MacEwan Bridge was measured to be 242.3 m. Using a late winter ice thickness of 1.0 m (table 3), a channel slope of 0.00037, and an overall roughness of 0.022, the computed discharge for a solid cover is 640 m^3/s. This is only 18 percent greater than the discharge computed by using the WSC technique and confirms the fact that considerable open water must have existed at the WSC gauge and downstream. It is interesting that 640 m^3/s is almost equal to the average of the open water discharge calculation and the calculation which uses the 1984 late winter ice thickness and roughness. This suggests that about 50 percent of the WSC section was open water; a very probable condition. On the basis of this discussion, an adopted formative discharge for the Moberly Rapids jam of between 540 m^3/s and 640 m^3/s does not seem improbable and the latter appears most reasonable.

Hydraulic Characteristics and Stability Analysis

Pariset et al. (1966) and Uzuner and Kennedy (1974) developed theories to predict the thickness of the equilibrium portion of a "wide channel" jam formed by internal collapse. Beltaos (1978) outlined the similarity of both approaches and suggested that if the porosity of the ice cover was the same above and below the water level, the stability equation for a "wide channel" jam could be given by

[3] $\rho_i(1-S_i)gt^2/2 = [W(\tau_i + \rho_i gSt)/2]-C_i t$

where μ is the dimensionless coefficient related to the internal friction of the ice cover, ρ_i the density of the ice, S_i the specific gravity of ice, t the jam thickness, W the channel width, τ_i the shear on the underside of the ice cover, g the acceleration of gravity, S the water surface slope, and C_i the cohesion (can be assumed to be negligible) of the ice cover.

The equilibrium stage H of an ice jam is composed of the thickness of the ice and depth on flow of water under the ice. This depth of flow is equal to the sum of the flow depth R_i associated with the ice cover and the flow depth R_b associated with the bed. Thus,

[3] $H = R_i + R_b + S_i t$

and considering the equilibrium of forces between the bed, the ice and the flow in a streamwise direction, the shear on the underside of the ice is given as

[4] $\tau_i = \rho gSR_i$

where ρ is the density of water.

Given a discharge Q at the time when the equilibrium thickness of the jam was established, the flow under the jam can be described by

[5] $Q = (1/n_o)(1/2)^{2/3}(H-S_it)^{5/3}\ WS^{1/2}$

where n_o has been previously defined and is related to both Manning's roughness coefficient of the underside of the ice cover and the bed as shown in equation [2].

Assuming that the average velocities in the flow area associated with the ice cover and the bed are equal, then

[6] $R_i/R_b = (n_i/n_b)^{2/3}$

Following Beltaos (1978), and combining equations [3] and [4] produces one equation with μ, τ_i, and R_i as the three unknowns. Combining equations [2], [3], [5] and [6] produces another equation with t and R_i as unknowns. This results in an indeterminate set of equations with three unknowns and only two equations. The only way to close the system is by directly measuring the thickness or the roughness of the jam. To date, this has proven impossible at Fort McMurray.

There are some alternatives to the above, but all involve some limiting assumptions. Firstly, one can assume the thickness of the cover is reflected by the unsubmerged thickness of the shear walls. This results in a higher estimate of the roughness and the dimensionless coefficient at internal friction. Second one can assume that all of the observed jams on the Athabasca River in the Fort McMurray area have similar roughness and use an ice roughness of 0.072 as reported by Andres (1980) and Andres and Doyle (1984). One can then go on to compute the thickness and the subsequent dimensionless coefficient of internal friction.

Table 5 illustrates the ranges of measured, assumed, and computed variables which characterize the documented jam. Assuming an average thickness of 4.1 m (on the basis of the observed shear walls) results in a computed ice roughness of 0.09 to 0.11 (depending on discharge) and a dimensionless coefficient of internal friction of 1.5. Both appear to be somewhat high, compared to previous work. This is to be expected

because the observed thickness is only the lower limit. Assuming an ice roughness of 0.072, results in a computed ice thickness of 4.5 to 4.7 m, depending on discharge. This appears to be a reasonable range of values, given the observed shear walls. The dimensionless coefficient of internal friction associated with this assumption varies between 1.2 and 1.3, slightly closer to the previously reported values.

From table 5 it is evident that the dimensionless coefficient of internal friction is fairly insensitive to changes in discharge. With the total stage, H and the bed roughness remaining constant, the change in discharge affects only the change in the ice roughness. This in turn affects the computed value of the hydraulic radius associated with the bed and the ice cover. However, given the small depth of flow under the jam, small changes in the ice roughness have almost negligible effect on the hydraulic radius associated with the ice cover. Hence the shear stress on the cover does not change nor does the dimensionless coefficient of internal friction.

Table 5.
Summary of the Characteristics of the Moberly Rapids Jam

	Measured			Assumed			Computed					
Date	H(m)	W(m)	S(m/km)	$Q(m^3/s)$	t(m)	$n_i(s/m^{1/3})$	t(m)	$n_i(s/m^{1/3})$	R_i(m)	R_b(m)	$\tau_i(P_a)$	μ
April 10, 1984	6.4	445	0.80	540[a]	4.1[c]	-	-	0.11	1.9	0.7	14.9	1.5
					-	0.072[d]	4.7	-	1.5	0.6	11.8	1.2
				640[b]	4.1[c]	-	-	0.092	1.9	0.7	14.8	1.5
						0.072[d]	4.5	-	1.6	0.7	12.5	1.3

a discharge computed from recorded water levels at WSC gauge
b discharge computed from observed water levels at MacEwan Bridge
c average jam thickness from measured shear wall thicknesses
d most reliable estimate of historical ice jam roughness (Andres and Doyle, 1984)

SUMMARY AND CONCLUSIONS

Breakup Observations

Breakup observations were carried out in The Athabasca River basin between Whitecourt and Fort McMurray. As in other years, the Little Paddle River was one of the first basins to respond to melting. It began to show signs of activity as early as March 27, 11 days after melting was first evident at the Twin Lakes snow pillow and after only 22 C°-days of melting at Campsie. The Paddle River response was affected by outflows from the Paddle River Dam and a thermal breakup process had established itself prior to March 29. By March 31, the ice cover at Barrhead was gone. Breakup on the Pembina River at Jarvie did not occur until April 6, ten days after first signs of activity on the Little Paddle River.

In all respects, the breakup on the above mentioned rivers was characterized by low water levels, most likely due to the fact that the snow pack in the basins was about 35 percent of normal. It is evident that a snow pack of only 26 cm (52 mm of water equivalent at the Twin Lakes snow pillow) is simply insufficient to generate a substantial enough runoff to produce an eventful breakup in the triubtary basins of the Athabasca River.

Conditions were similar on the Athabasca River. Given the fact that almost negligible runoff was introduced from both the McLeod and Pembina Rivers, the Athabasca River had to generate its own breakup. As a result breakup was overmature and occurred in a piece-meal fashion. Unfortunately, sufficient observations could not be made to adequately describe it. It seems evident, however, that the reach between the Pembina River and the Town of Athabasca was first to respond, with breakup at Athabasca occurring on April 7 after 70 C°-days of melting at Slave Lake. By April 9, the breakup front had progressed downstream to La Biche River and by early in the day of April 10 it reached the mouth of the House River. An intact cover was observed from there to Point La Biche. Downstream at Point La Biche the ice went out on April 9 and

open water was evident as far downstream as Middle Rapids. Later that day, over a period of few hours, all the ice upstream of Grande Rapids moved downstream and by midnight, the breakup front arrived at Fort McMurray. It is not known whether the ice upstream of Rapides du Joli Fou took part in the run to Fort McMurray. A 6 m high ice jam formed upstream of the MacEwan Bridge but remained in place for only about two hours, after which it released and moved far enough downstream of Fort McMurray so as not to be flood hazard.

The 1984 breakup was characterized by an extremely low snow pack and no significant north-south temperature gradient in the Athabasca River basin. These conditions moderated the runoff from the upstream portion of the basin and prevented it from augmenting the surge related discharge caused by the downstream progression of the breakup front in the vicinity of Fort McMurray. As a result the ice runs were of only moderate intensity and the subsequent jams of limited height. Also, the relatively warm northern portion of the basin allowed for greater deterioration of the ice cover and hence a more rapid downstream progression of the breakup front without significant jamming.

Moberly Rapids Jam

During the 1984 breakup, a significant jam formed just upstream of MacEwan Bridge. It appeared to have a length of about 9 km, an average height of 6.4 m, and an average thickness of at least 4.1 m. The discharge at which the jam formed was difficult to define but was estimated to be in the order of 540 to 640 m^3/s.

Stability analysis at the jam showed that an upper limit of about 0.10 can be placed on the Manning's roughness of the ice cover if a thickness of 4.1 m is adopted. A more realistic thickness of 4.6 m results if it is assumed the Manning's roughness of the ice cover is 0.072. This supports the previous assertions that such a roughness can be used to characterize most ice jams that form on the Athabasca River in the Fort McMurray area.

Finally, the dimensionless coefficient of internal friction was found to vary between 1.2 and 1.5. The upper value reflects a minimum possible ice thickness and therefore is probably on the high side. The smaller value is very close to values previously reported and results when an ice roughness of 0.072 is adopted.

From the perspectives of flood damages, the discharge was simply not sufficient to produce a large enough jam to cause significant flooding. Even if the jam had formed downstream at the mouth of the Clearwater River it is unlikely the peak water levels would have exceeded 244 m.

REFERENCES

Alberta Environment 1984. Water supply review and snow survey summary. Prepared by the Alberta River Forecast Centre and the Survey Branch, Edmonton, Alberta.

Andres, D.D., and Doyle, P.F. 1984. Analysis of breakup and ice jams on the Athabasca River at Fort McMurray, Alberta. Canadian Journal of Civil Engineering, Volume 11, No. 3, pp. 444-458.

Andres, D.D., and Rickert, H.A. 1984. Observations of the 1983 breakup in the Athabasca River basin upstream of Fort McMurray, Alberta. Report SWE 84-1 Civil Engineering Department, Alberta Research Council, Edmonton, Alberta.

Beltaos, S. 1978. Field investigations of river ice jams, Alberta Research Council Contribution Series No. 881, Proceedings, International Association of Hydraulic Research Symposium on Ice Problems, Part II, Lulea, Sweden, pp. 351-371.

Blench, T. 1964. Flood protection proposals for McMurray. T. Blench and Associates report for Alberta Environment, Edmonton, Alberta.

Doyle, P.F., and Andres, D.D. 1979. 1979 breakup and ice jamming on the Athabasca River near Fort McMurray. Report SWE 79-05. Civil Engineering Department, Alberta Research Council, Edmonton, Alberta.

Pariset, E., Hauser, R., and Gagnon, A. 1966. Formation of ice covers and ice jams in rivers. ASCE Journal of the Hydraulics Division, 92(HY6), pp. 1-24.

Uzuner, M.S., and Kennedy, J.F. 1974. Hydraulics and mechanics of river ice jams. Iowa Institute of Hydraulic Research, The University of Iowa, Iowa City, Iowa, Report No. 161.

REFERENCES

Alberta Environment 1984. Water supply review and snow survey summary. Prepared by the Alberta River Forecast Centre and the Survey Branch, Edmonton, Alberta.

Andres, D.D., and Doyle, P.F. 1984. Analysis of breakup and ice jams on the Athabasca River at Fort McMurray, Alberta. Canadian Journal of Civil Engineering, Volume 11, No. 3, pp. 444-458.

Andres, D.D., and Rickert, H.A. 1984. Observations of the 1982 breakup in the Athabasca River basin upstream of Fort McMurray, Alberta. Report SWE 84-1 Civil Engineering Department, Alberta Research Council, Edmonton, Alberta.

Beltaos, S. 1978. Field investigations of river ice jams, Alberta Research Council Contribution Series No. 881, Proceedings, International Association of Hydraulic Research Symposium on Ice Problems, Part II, Lulea, Sweden, pp. 351-371.

Blench, T. 1964. Flood protection proposals for McMurray. T. Blench and Associates report for Alberta Environment, Edmonton, Alberta.

Doyle, P.F., and Andres, D.D. 1979. 1979 breakup and ice jamming on the Athabasca River near Fort McMurray. Report SWE 79-05. Civil Engineering Department, Alberta Research Council, Edmonton, Alberta.

Pariset, E., Hausser, R., and Gagnon, A. 1966. Formation of ice covers and ice jams in rivers. ASCE Journal of the Hydraulics Division, 92(HY6), pp. 1-24.

Uzuner, M.S., and Kennedy, J.F. 1974. Hydraulics and mechanics of river ice jams. Iowa Institute of Hydraulic Research, The University of Iowa, Iowa City, Iowa, Report No. 161.